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# MINIMIZING AND MANAGING POTENTIAL IMPACTS OF INDUCED-SEISMICITY FROM CLASS II DISPOSAL WELLS: PRACTICAL APPROACHES

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## EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program regulates injection of fluids related to oil and gas production as Class II injection wells for the protection of underground sources of drinking water (USDW). Unconventional resources and new technologies, such as horizontal drilling and advanced completion techniques, have expanded the geographic area for oil and gas production activities resulting in a need for Class II disposal wells in some areas previously considered unproductive.

Recently, a number of low to moderate magnitude (<5.0) earthquakes<sup>1</sup> were recorded in areas with Class II disposal related to shale hydrocarbon production. To address the concern that induced seismicity could interfere with containment of injected fluids and endanger drinking water sources, EPA's Drinking Water Protection Division requested the UIC National Technical Workgroup (NTW) develop a report with practical tools to address injection-induced seismicity. This report used the existing Class II regulatory framework to provide possible strategies for managing and minimizing the potential for significant injection-induced seismic events. The report focused on Class II disposal operations as these wells have been suspected of inducing seismicity. In formulating these strategies, the NTW conducted a technical literature search and review. Additionally, the NTW evaluated four recent case examples (Arkansas, Ohio, Texas and West Virginia) considering data availability, and variations in geology and reservoir characteristics.

Disposal wells are one of a number of historic causes of human activity-induced earthquakes. Others include construction of dams and water reservoirs, mining activities, oil and gas production, and geothermal energy production. Evaluation of induced seismicity is not new to the UIC program. This report is intended to describe for UIC program management the current understandings related to induced seismicity within the existing Class II regulatory framework for Class II disposal. The Class II UIC program does not have regulations specific to seismicity but rather includes discretionary authority that allows additional conditions to be added to the permit on a case-by-case basis as well as additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.<sup>2</sup> Legal and policy considerations of Class II regulations are outside the scope of this technical report.

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<sup>1</sup> Information on earthquake terms is included under *Glossary terms*, or can be linked to through *Appendix J; Educational Websites* (J-12).

<sup>2</sup> 40 CFR §144.12(b) and 40 CFR §144.52(a)(9)

1 The NTW confirmed the following components are necessary for significant injection-induced  
2 seismicity: (1) stressed faults<sup>3</sup>, (2) pressure buildup from disposal activities, and (3) a pathway  
3 for increased pressure to communicate with the fault. The NTW noted that no single  
4 recommendation addresses all of the complexities related to injection-induced seismicity,  
5 which is dependent on a combination of site geology, geophysical and reservoir characteristics.  
6 An absence of historical seismic events in the vicinity of a disposal well does not provide  
7 assurance that induced seismicity will not occur; however, this absence may be a supportive  
8 indicator of induced seismicity if events occur following activation of an injection well. Proof of  
9 induced seismicity is difficult to achieve, but it is not a prerequisite for prudent action.

10 The NTW developed a decision model (Figure 1) to inform UIC management about site  
11 assessment strategies and practical approaches for assessing the three fundamental  
12 components. The model begins with considerations for a site assessment dependent on  
13 location specific conditions, because understanding the geologic characteristics of a site is an  
14 essential step in evaluating the potential for injection-induced seismicity. Monitoring,  
15 operational and management approaches with useful practical tools for managing and  
16 minimizing injection-induced seismicity are recommended. The NTW also found that basic  
17 petroleum reservoir engineering practices coupled with geosciences information can provide a  
18 better understanding of reservoir and fault characteristics and offer many ways of analyzing  
19 injection-induced seismicity concerns, possibly identifying anomalies that warrant additional  
20 site assessment or monitoring. The NTW recommends future research consider a practical  
21 multidisciplinary approach and a holistic assessment addressing disposal well and reservoir  
22 behavior; geology; and area seismicity.

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<sup>3</sup> Stressed fault as used in this report denotes a fault with the potential to cause a significant earthquake.

## 1 INTRODUCTION

2 The Environmental Protection Agency (EPA) Underground Injection Control (UIC) program,  
3 authorized by the Safe Drinking Water Act, regulates injection of fluids related to oil and gas  
4 production as a Class II well, for the protection of underground sources of drinking water  
5 (USDW). Class II disposal wells have been used to dispose of oil and gas related wastes for  
6 decades with very few associated seismic events. However, unconventional resources and new  
7 technologies, such as horizontal drilling and advanced completion techniques, have expanded  
8 the geographic area for oil and gas production activities resulting in a need for Class II disposal  
9 wells in some areas previously considered unproductive.

10 Recently, a number of low to moderate magnitude (<5.0) earthquakes<sup>4</sup> were recorded in areas  
11 with Class II disposal related to shale hydrocarbon production. To address the concern that  
12 induced seismicity could interfere with containment of injected fluids and endanger drinking  
13 water sources, EPA's Drinking Water Protection Division requested the UIC National Technical  
14 Workgroup (NTW) develop recommendations for the consideration of UIC management  
15 ([Appendix A](#)). The Induced Seismicity Working Group (WG) of the NTW was formed in June  
16 2011 to spearhead development of a report containing recommendations<sup>5</sup> of possible  
17 strategies for managing or minimizing significant<sup>6</sup> seismic events associated with induced  
18 seismicity in the context of Class II disposal well operations.

19 Disposal wells are one of a number of historic causes of human activity-induced earthquakes.  
20 Others include construction of dams and water reservoirs, mining activities, oil and gas  
21 production, and geothermal energy production. Evaluation of induced seismicity is not new to  
22 the UIC program. Although not a major part of this effort, seismicity associated with hydraulic  
23 fracturing (HF) was addressed in several of the literature sources, with which the WG agreed  
24 with the conclusions that HF has a low likelihood of inducing significant seismicity. This report  
25 is intended to describe for UIC program management the current understandings related to  
26 induced seismicity within the existing Class II regulatory framework for Class II disposal. The  
27 Class II UIC program does not have regulations specific to seismicity but rather includes  
28 discretionary authority that allows additional conditions to be added to the permit on a case-

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<sup>4</sup> Information on earthquake terms is included under *Glossary terms*, or can be linked to through *Appendix J; Educational Websites* (J-12).

<sup>5</sup> Although this project focused specifically on Class II disposal wells, many of the recommendations discussed in this report may be applicable to other well classes.

<sup>6</sup> For the purposes of this report, the Induced Seismicity Working Group considers "significant" seismic events to be those of magnitude to potentially endanger underground sources of drinking water.

by-case basis as well as additional requirements for construction, corrective action, operation, monitoring, or reporting (including closure of the injection well) as necessary to protect USDWs.<sup>7</sup> In the case studies reviewed for this report, UIC Director used this discretionary authority to manage and minimize seismic events. Legal and policy considerations of Class II regulations are outside the scope of this technical report.

Class II injection wells include injection for the purpose of enhanced oil recovery or oil and gas production wastewater disposal. Injection related to enhanced recovery projects generally poses less potential to induce seismicity than a brine disposal well because injection and production volumes partially negate each other during enhanced recovery unlike disposal wells. Given the greater potential for pressure buildup and recent seismic activity, both associated with Class II disposal wells, this WG effort focused on recommendations to manage or minimize induced seismicity associated with oil and gas related Class II disposal wells.

The primary intent of this effort was the development of a practical tool that provides possible site assessment considerations for minimizing or addressing significant injection-induced seismicity. The considerations included were those identified as pertinent by the WG, though other factors may also be appropriate depending on site-specific situations. This practical tool also provides operational and monitoring options for managing injection-induced seismicity, and provides a decision model supported by an extensive literature review and four case histories, which considered earthquake history, proximity of disposal well to these events, and disposal well behavior.

Many of the recommendations discussed in this report are applicable to other well classes. For example, disposal activities also occur in Class I hazardous and non-hazardous wells, and various Class V wells. The US Department of Energy and International Energy Agency have authored several publications dealing with specific Class V geothermal seismicity issues. The WG reviewed a number of publications as part of the literature survey for this report ([Appendix K](#)). Conclusions from some of these reports were applicable to the Class II injection-induced seismicity project. The reservoir engineering approaches used to evaluate Class II case study wells may also provide a tool for other well classes outside the scope of this project.

## INJECTION-INDUCED SEISMICITY PROJECT OBJECTIVES

The WG analyzed existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

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<sup>7</sup> 40 CFR §144.12(b) and 40 CFR §144.52(a)(9)

1. What parameters are most relevant to screen for injection-induced seismicity?
2. Which siting, operating, or other technical parameters are collected under current regulations?
3. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection-induced seismic activity?
4. What other information would be useful for enhancing a decision making model?
5. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection-induced seismicity?
6. What lessons have been learned from evaluating case histories?

#### WORKING GROUP TASKS

The UIC NTW was tasked by UIC management with developing a report including technical recommendations to manage or minimize significant levels of injection-induced seismicity.

The UIC NTW utilized the following approaches to address the objectives:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Preparation of a decision model
3. Applicability of pressure transient testing and/or pressure monitoring techniques
4. Summary of lessons learned from case studies
5. Recommendations for measurements or monitoring techniques for higher risk areas
6. Applicability of conclusions to other well classes
7. Recommendations for specific areas of research needed

#### WORKING GROUP APPROACH

The WG adopted the following strategy to develop the technical recommendations:

1. Compile and review historical and current scientific literature including ongoing projects and material associated with upcoming reports on injection-induced seismicity
2. Select and study recent case examples of Class II brine disposal wells suspected of inducing seismicity and provide a summary of lessons learned for the following areas:
  - a. North Texas
  - b. Central Arkansas
  - c. Braxton County, West Virginia
  - d. Youngstown, Ohio
3. Summarize geology applications
4. Apply reservoir engineering methods

5. Develop a Decision Model with technical recommendations
6. Consult with US Geological Survey (USGS) seismologists on the potential for deep stress field measurements and USGS earthquake information as screening tools (See [Appendix M](#))
7. Compare data collected under existing UIC requirements to relevant information needed for assessment of injection-induced seismicity
8. Solicit review by EPA's UIC NTW and subject matter contributors from state agencies, academia, and industry including researchers from Southern Methodist University (SMU); Stanford University; and the Jackson School of Geosciences, University of Texas at Austin; Arkansas Geological Survey; Oklahoma Geological Survey; USGS; select members of the National Academy of Science Committee on Induced Seismicity Potential in Energy Technologies; Pinnacle Technologies; Chesapeake Energy; Hess Corporation; and state regulators with the Railroad Commission of Texas, Arkansas Oil and Gas Commission, West Virginia Department of Environmental Protection Office of Oil and Gas, and Colorado Oil and Gas Conservation Commission

## TERMINOLOGY USE

A glossary with complete definitions is included on page 34. Most of these definitions come from a USGS online glossary<sup>8</sup>.

For this report:

- All earthquakes resulting from human activities are referred to as induced
- Magnitude will refer to the values reported by USGS Advanced National Seismic System
- Reservoir engineering methodologies used in this document adhere to practices and equations commonly presented in petroleum engineering literature

## GEOSCIENCE FACTORS RELATED TO INJECTION-INDUCED SEISMICITY

The NTW identified three components necessary to cause injection-induced seismicity: a fault<sup>9</sup> under stress, formation pore pressure buildup from injection of fluids, and an avenue of communication between the area of pressure buildup and the stressed fault. Understanding the geologic characteristics of a site is therefore essential to evaluating the potential for injection-induced seismicity.

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<sup>8</sup> <http://earthquake.usgs.gov/earthquakes/glossary.php> terms used in USGS maps;  
<http://earthquake.usgs.gov/learn/glossary/> general earthquake terms

<sup>9</sup> Fault may refer to a single or a zone of multiple faults and fractures

1 Most reservoirs or disposal zones occur within sedimentary rocks deposited according to basic  
2 stratigraphic processes in geologic environments of the past. Depositional environments and  
3 source materials control the initial quality and quantity of space (porosity) in reservoirs and the  
4 connections among those pore spaces (permeability). Burial and later chemical changes will  
5 generally deform and consolidate the sediments, decrease the porosity and diminish the  
6 permeability. However, some changes following deposition can increase porosity and  
7 permeability (e.g., dissolution of limestone in karstic settings).

8 In simplest terms, porosity is the primary storage capacity of the reservoir, and permeability  
9 determines how fluids and pressure are transmitted within the reservoir. Generally, deeper  
10 rocks have less permeability and porosity than shallow rocks. When movement or deformation  
11 occurs after initial deposition, a brittle rock will break during the deformation process creating  
12 fractures. A rock type that is not brittle will deform rather than break. Generally,  
13 dolomite/limestone is the one of the most brittle and clay/shale is the most flexible/ductile  
14 sedimentary rock types. Porosity, which develops after initial deposition, is known as  
15 secondary porosity and includes fracture porosity in rocks that have been fractured.

16 The distribution and quality of porosity and permeability within the disposal zone are critical for  
17 understanding how efficiently the formation will accept additional fluid. The area of increased  
18 pore pressure will be smaller in formations that allow fluids to move through the rock easily  
19 and quickly dissipate pore pressure versus formations with restricted fluid movement. Vertical  
20 and lateral variations in permeability and porosity are common in sedimentary rocks, as are  
21 lateral variations in thickness of porous injection zones.

22 Class II disposal well regulations are designed to protect USDWs by ensuring an upper confining  
23 layer or layers isolate the disposal zone from the USDW. However, in areas where injection-  
24 induced seismicity is a concern, the presence of a lower confining zone may serve to restrict  
25 pressure communication with underlying faults. Heterogeneities and a lower confining layer  
26 can also substantially affect the size of pressure buildup areas from disposal operations by  
27 allowing pressures to dissipate over larger distances or by confining pressures to the injection  
28 zone. The nature of porosity and permeability in the injection formation is of fundamental  
29 concern to induced seismicity evaluations because of its importance to pore pressure buildup.

30 Pressure and permeability are critical to understanding if pressure influence from the injection  
31 site is likely to communicate with a stressed fault zone. For example, pressure influence from  
32 disposal operations may encounter a fracture system parallel to the fault trend and  
33 subsequently reach the fault. [Appendix I](#) provides an example of rapid long distance  
34 transmission of pressure in a heterogeneous reservoir, without inducing seismicity.

Most of the literature and case examples of possible disposal induced seismicity described in this report, as well as events of natural origin, are related to stressed faults in basement rocks. Basement rocks are those igneous or metamorphic rocks that underlie the sedimentary rocks of continents. The contact between basement rocks and overlying younger strata is almost always an erosional surface (Narr et.al, 2006). Basement rocks usually have no effective primary permeability or porosity; however, later weathering or movement can result in fractures and erosional features along the upper surface of basement rocks creating secondary porosity. Faulting of basement rocks can result in fracture porosity and permeability along the fault zone. Some faults occur only in overlying sedimentary rocks. Basement faults may or may not extend into the overlying sedimentary section. Basement faults that are active after deposition of overlying material can extend upward into overlying rock.

Regional evaluations for purposes of assessing induced seismicity potential should consider the geologic history (structural, depositional, geochemical, etc.), earthquake history, and fault trends. This review should give particular attention to features such as major lineaments, faults (including but not limited to basement faults), fractured formations, and deformation. Tectonic forces acting from plate margins create a stress field at depth across the entire continent.

The history of seismic events in the region and the immediate area will indicate if the area continues to be active. However, seismicity may occur in areas with no previous recorded seismic events. The absence of recorded events may be related to a lack of seismometers or an event trigger. A recent history of tectonic stress or seismic history in a regional area around the site may be an indicator of significantly stressed faults in the area.

## REVIEW OF SCIENTIFIC LITERATURE

### LITERATURE SOURCES

Injection-induced seismicity has been documented in many reports from 1968 to 2011. The WG compiled and reviewed an extensive reference list included in [Appendix K](#). Additionally, relevant references and National Academy of Science committee presentations related to injection-induced seismicity are included in the References section of the main body and Appendix H, respectively. Some researchers contacted as part of this project are preparing reports of recent findings and anticipate publication in 2012 (Hayward and Stump).

The USGS Advanced National Seismic System (ANSS) maintains the largest U.S. database of earthquake events. The USGS National Earthquake Information Center (NEIC) maintains several other catalogs. The catalogs generally include the location accuracy of the event. Catalogs may vary, but are an important consideration for induced seismicity analyses. USGS, state geologic



1 agencies and universities may also collect and/or host earthquake information on their  
2 websites. There may be inconsistencies between databases, such as detection threshold,  
3 calculated epicenter, depth, magnitude determination or regional area covered. It should be  
4 noted that the expansion or development of regional seismometer networks may measure  
5 seismic activity at a lower magnitude threshold than previously recorded, creating the  
6 appearance of increased seismicity.

## 7 THE FUNDAMENTAL THEORY OF INJECTION-INDUCED SEISMICITY

8 The Mohr-Coulomb failure criterion is the fundamental rock mechanics model describing the  
9 fracturing or motion along a fault. The Mohr-Coulomb criterion uses the tectonic stresses on a  
10 fault, the frictional resistance of the fault materials, and the fluid pressure within the fault to  
11 determine whether or not that fault will slip. In the case of injection-induced seismicity, fluid  
12 pressures are raised within the fault, which in turn reduces the frictional resistance along the  
13 fault. Lowering the frictional resistance, means that stresses that were once not high enough to  
14 cause failure may now be high enough to cause failure.

15 Fluid injection may relay increased fluid pressures to a fault zone at distance from the injection  
16 point. Pressure buildup transference can occur when the disposal zone is in hydraulic  
17 communication with the fault zone. Lateral and vertical reservoir pathways to a stressed fault  
18 could include natural rock fractures, injection-induced fractures, other faults or possibly other  
19 mechanisms specific to the disposal zone.

20 Earthquake magnitude is roughly proportional to the length or area of fault slip (Wells and  
21 Coppersmith, 1994). For example, the 7.1 magnitude 'World Series Earthquake' in Loma Prieta,  
22 California, in 1989, was caused by the slippage of a twenty-two mile long fault segment of the  
23 San Andreas Fault system (US Geological Survey, 1995). In contrast to natural earthquakes,  
24 seismic events from hydraulic fracturing of shale formations typically range in magnitude from  
25 -4 and 0 (Warpinski et al., 2012), which correspond to less than one millimeter of slip on a  
26 section of rock around a half meter long (Das and Zoback, 2011).

## 27 POSSIBLE CAUSES OF INDUCED SEISMICITY

28 Seismicity induced by human activities has been extensively documented. Seismic events have  
29 been associated with mining, lake filling, geothermal energy related injection, oil and gas  
30 production activities, and disposal wells. Davis and Frohlich (1993), Nicholson and Wesson  
31 (1990; 1992), and Suckale (2009, 2010) studied case histories of potential oil and gas related  
32 induced seismicity across the U.S. and Canada. Several waste disposal case studies were  
33 investigated including Rocky Mountain Arsenal, Colorado; and two locations in far northeastern  
34 Ohio (Ashtabula and Cleveland occurring from 1986 - 2001). Opposing conclusions were drawn

on whether the earlier Ohio seismicity was related to injection (Gerrish and Nieto, 2003; Nicholson and Wesson, 1990). Several studies conclude that the Rocky Mountain Arsenal seismicity was caused by injection (Davis and Frohlich, 1993; Nicholson and Wesson, 1990; Nicholson and Wesson, 1992; Suckale, 2009, 2010). At the Rocky Mountain Arsenal, the largest three earthquakes, with magnitudes between 4.5 and 4.8 occurred over one year after injection stopped.

In March 1962, injection of waste fluids from chemical manufacturing operations at the Rocky Mountain Arsenal was initiated into a fractured crystalline basement rock beneath the facility. Initial injection exceeded the formation fracture pressure from March 1962 through September 1963 when the surface pump was removed leaving injection under hydrostatic pressure. Pumps were once again used for injection from April 1965 through February 1966 when injection ceased. Seismicity started eight km from the well on April 24, 1962, with magnitudes ranging from 1.5 to 4.4 from 1962 through 1966, and three earthquakes of magnitude ranging from 5.0 to 5.4 in 1967. Subsequent investigations identified a major fault near the well, and showed a direct correlation between increases in bottomhole pressure during injection and the number of earthquakes using Rank Difference Correlation (Healy et al., 1968; Hsieh and Bredehoeft, 1981; Raleigh, 1972).

From 1969 through 1974, the relationship between seismicity and Class II enhanced recovery injection operations at the Rangely field in Colorado were studied (Raleigh, 1972; Raleigh et al., 1976). Reservoir pressures were controlled by varying injection and withdrawal from injection wells within the Rangely field to determine the relationship between pressure and induced seismicity. Fourteen seismometers deployed throughout the area recorded events ranging from -0.5 to 3.1 in magnitude, which occurred in clusters in both time and space. Most of these events were below the threshold that is typically felt by humans (magnitude 2.5)<sup>10</sup>. Seismometer data and injection pressure and volume data coupled with modeling confirmed that earthquakes were triggered through an increase in pore pressure. Frictional strength along the fault varied directly with the difference between total normal stress and fluid pressure (Raleigh et al., 1976). Unusual features in this case included measurable response to fluid pressure along one part of the fault; recordable compartmentalization within the reservoir around the fault; and verification that maintaining the reservoir pressure below a calculated threshold stopped the seismicity (Raleigh, 1972; Raleigh et al., 1976).

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<sup>10</sup> Microseismic and small seismic events may occur but go undetected or unfelt and pose no significant risk to human health or USDWs.

Numerous earthquakes were induced by Class V disposal operations being used to control salinity in Paradox Valley, Colorado (Ake, 2002 and 2005; Block, 2011; and Mahrer, 2005). Seismicity is being managed using intermittent injection periods, injection rate control, and extensive seismic monitoring. Additionally a second Class V disposal well located several miles from the existing well is being evaluated by the U.S. Bureau of Reclamation in response to an expanding area of seismicity. The existing well is required for salinity control and operates above fracture pressure. More information is included in Appendix J.

A number of informative references on induced seismicity and enhanced geothermal systems exist that cover a broad range of issues and outline many avenues of additional research needed (Hunt and Morelli, 2006; Majer et al., 2007; and Majer et al., 2011). These authors documented the combination of monitoring techniques with operational parameters to control seismicity. However, the causes of geothermal-related seismicity may be different than the seismicity induced by brine disposal injection. For example, thermal stress, in addition to pressure buildup, plays a key role in geothermal seismicity, but may be of limited applicability to brine disposal wells.

Though rare, hydraulic fracturing (HF) induced seismicity is possible if the HF encounters a stressed fault. The process of HF cracks the rock formation near the wellbore to enhance oil and gas production, causing microseismic events that generally are not felt ( $\leq 2.5$  magnitude) at the surface. Several studies documented microseismicity (magnitude  $< 1$ ) caused by HF (Das and Zoback, 2011; Phillips et al., 2002; Warpinski, 2009 and 2012). Recording these very low magnitude seismic events (microseismicity) requires the use of downhole seismometers in nearby wells (Warpinski, 2009). However, two recent reports published by the Oklahoma Geological Survey and Cuadrilla Resources documented seismic events up to magnitude 2.8 due to HF communication with stressed faults (de Pater and Baisch, 2011; Holland, 2011).

The “pressure footprint” of an injection well is related to the injection rate, duration of the injection period and transmissibility of the reservoir (Lee et al., 2003). Class II disposal wells typically inject for months or years and generate large “pressure footprints” with no offset production of fluids. In comparison, the “pressure footprint” from HF is a short term event followed by extraction of fracture fluids and hydrocarbons, resulting in a decrease in pressure within the formation where the fracture occurred. Additionally, the “pressure footprint” of HF is generally contained within the fracture growth or fracture propagation area (Gidley et al., 1990).

## DETERMINATIONS OF INJECTION-INDUCED SEISMICITY

Nicholson and Wesson (1990) stated that induced seismicity determinations rely on three primary characteristics of earthquake activity:

1. Geographic association between the injection zone and the location of the earthquake
2. Exceedance of theoretical friction threshold for fault slippage
3. Disparity between previous natural seismicity and subsequent earthquakes following disposal with elevated pressures

Davis and Frohlich (1993) developed a practical approach for evaluating whether seismic events were induced by injection based on similar characteristics stated by Nicholson and Wesson (1990) e.g., history of previous seismic events, proximity in time and space, and comparison of critical fluid pressures. The Davis and Frohlich approach utilizes a series of fundamental questions to evaluate the likelihood of induced seismicity. These questions are outlined below:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypocenter locations sufficient to encourage seismicity?

Although these approaches are qualitative and do not result in proof of injection-induced seismicity, they may be useful to UIC Directors. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for prudent action to further assess the possibility of induced seismicity by acquiring more data.

## CASE STUDY RESULTS

A total of four geographic areas of suspected injection-induced seismicity were selected by the WG for more detailed evaluation. These cases studies were selected from areas where disposal wells were linked with recent seismic events. Initially, North Texas, Central Arkansas, and Braxton County, West Virginia areas were selected. The Youngstown, Ohio, area was included late in the project because a disposal well was the suspected cause of a series of recent seismic events.

Initially, the WG identified disposal wells located in the vicinity of recent seismic events in the selected geographic areas. In order to compare well activities to seismic events, a radial area around the well was used to gather seismic data. Historic seismic events for the cases were derived from six different database catalogs. These external databases are discussed in more detail in Appendix L. A radius between five and twelve miles around each case study well was selected based on the spacing density of the existing seismometers and location of the seismicity in the immediate area of the wells.

The specific strategies used by the WG for evaluating the cases included engaging researchers who had studied two of the cases, reviewing available geologic structure maps, acquiring specific injection well data from the four state regulatory agencies and communicating with a well operator. A reservoir engineering analysis based on the collected well data was also performed on each case study well. Additional geoscience background and the results of EPA's reservoir engineering analysis on these cases are discussed in greater detail in the appendix specific to each case study (Appendices D, E, F, and G).

Each case is discussed below in terms of a background summary relating to the seismic activity and a description of how the case was evaluated by the WG. A summary of the common characteristics and lessons learned from the case studies is included following the case study summaries.

## NORTH TEXAS AREA

Several small earthquakes occurred in the central part of the Dallas-Fort Worth metroplex near the Dallas-Fort Worth International Airport (DFW) on October 31, 2008, and near the town of Cleburne on June 2, 2009. Both areas are located in north central Texas, in the eastern portion of the Barnett shale play. Prior to 2008, no earthquakes had been reported within 40 miles of the recent DFW and Cleburne events. Although Barnett shale hydrocarbon production was discovered in Wise County in 1981, extensive drilling into the Barnett shale began in the late 1990s with the advancement of technologies.

The Railroad Commission of Texas (RRC) standard permit application package incorporated some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (disposal zone, maximum allowable injection rate and surface pressure). In addition, an annual report filed by the operator provides monthly injection volumes and pressure data. WG review

1 of the annual injection reports indicated that the well operated within the permitted pressure  
2 limits. One of the Cleburne area disposal wells was dually permitted as a Class II and Class I  
3 disposal well by different regulatory agencies. UIC Class I well requirements include conducting  
4 annual falloff tests. These tests provided reservoir characteristics and pressures for compliance  
5 with the Class I well permit and were not required in response to area seismicity. WG reviewed  
6 the available falloff tests that confirmed the Ellenburger disposal interval was naturally  
7 fractured. More details on this case study are available in Appendix D.

8 Following the 2008 and 2009 events, the RRC identified active disposal wells in the area for  
9 further evaluation as to the possible cause of seismic events due to the wells' proximity to the  
10 epicenters of seismic events and the absence of seismicity prior to initiation of disposal. RRC  
11 opened a dialogue with the operators of the suspect disposal wells, resulting in the voluntary  
12 cessation of two wells, one in the DFW area and one in the Cleburne area, in August 2009 and  
13 July 2009 respectively. Since the deactivation of the two wells, the frequency and magnitude of  
14 seismic events has substantially decreased.

15 The RRC subsequently reviewed its permit actions for these wells and other wells in the area in  
16 an effort to determine if the activity could have been predicted. No indications of possible  
17 induced seismicity were found in these reviews. RRC also inspected the area to verify there  
18 were no resulting public safety issues from these events. In follow-up, the RRC consulted with  
19 industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern  
20 Methodist University, and Texas A&M University, and continues to monitor developments and  
21 research related to injection-induced seismicity.

## 22 CENTRAL ARKANSAS AREA

23 From 2009 through 2011, a series of minor earthquakes occurred in the Fayetteville shale play  
24 near the towns of Guy and Greenbrier in Faulkner County, Arkansas. Regionally, the Enola area  
25 located approximately nine miles southeast of Greenbrier experienced a swarm of earthquakes  
26 starting in 1982<sup>11</sup>.

27 The Arkansas Oil and Gas Commission (AOGC) standard permit application package  
28 incorporated site assessment, well construction and completion information along with other  
29 supporting documentation to demonstrate the protection of USDWs. Site assessment  
30 documentation included surface maps, location plats, disposal depths and inventory of offset

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<sup>11</sup> Arkansas Geological Survey, 2007, Enola Swarm Area-Faulkner County, Arkansas: GH-EQ-ENOLA-002.

1 wells within the area of review. Several of the permit applications contained detailed geologic  
2 information, such as a narrative, structure map, type log and additional interpretive data. Well  
3 construction details provided to the state included well specifics (casing, cement information,  
4 perforations, and completion information) and monitored disposal conditions (disposal zone,  
5 maximum allowable injection rate and surface pressure). In addition, an annual report filed by  
6 the operator provides monthly injection volumes and pressure data. For one disposal well  
7 closest to the Enola area earthquakes, AOGC also required pressure falloff testing, additional  
8 seismic monitoring and intermittent injection during the permitting process. WG review of the  
9 annual injection reports indicated that the Enola area well operated within the permitted  
10 pressure limits.

11 In October 2009, three and a half months after injection was initiated, earthquake activity  
12 began in the immediate Greenbrier area. To investigate the earthquakes, the AOGC worked  
13 with the Arkansas Geological Survey (AGS) and the University of Memphis Center of Earthquake  
14 Research and Information (CERI) and additional seismographs were deployed. In December  
15 2010, following increased frequency and higher magnitude earthquakes, AOGC established a  
16 moratorium on the drilling of any new Class II disposal wells in an area surrounding and the  
17 immediate vicinity of the increased seismic activity. AOGC also required the operators of the  
18 seven existing Class II disposal wells operating in the moratorium area to provide bi-hourly  
19 injection rates and pressures for a period of six months, through July 2011. During the  
20 moratorium period, the AGS and CERI analyzed the injection data and seismic activity to  
21 determine if there was a relationship.

22 In late February 2011, following a series of larger magnitude earthquakes, the operators of  
23 three disposal wells nearest to the seismic activity voluntarily terminated well operations prior  
24 to the issuance of an AOGC cessation order issued on March 4, 2011. In July 2011, following  
25 the conclusion of the moratorium study, AOGC established a revised permanent moratorium  
26 area in which no additional Class II disposal wells would be drilled and required four of the  
27 original seven disposal wells to be plugged. The revised moratorium area was based on the  
28 trend of the Guy-Greenbrier fault, identified as the cause of the seismic activity. The operators  
29 of three of the wells voluntarily agreed to plug the subject disposal wells and were  
30 consequently not parties to the Commission July 2011 Hearing. Following the July 2011  
31 Commission Hearing, the Commission issued an order to the operator of the fourth disposal  
32 well to plug their well. The final moratorium ruling was authorized on February 17, 2012.

33 AOGC now requires UIC permit applications to provide technical justification for the location of  
34 wells within the Moratorium Zone or within a specified distance from the Regional Deep Faults.  
35 Operators of Class II disposal and commercial disposal wells must submit injection and pressure  
36 information on a daily (or more frequent) basis, from monitoring devices approved by AOGC.

1 Additionally, AOGC is studying the feasibility of establishing a permanent seismic array in the  
2 Fayetteville shale development area to monitor future disposal well operations, thereby  
3 creating an “early warning” system for developing seismic activity, and possibly allowing more  
4 time to develop management strategies. More details on this case study are available in  
5 Appendix E.

#### 6 BRAXTON COUNTY, WEST VIRGINIA

7 In April 2010, a series of earthquakes ranging in magnitude from 2.2 to 3.4 began in Braxton  
8 County, West Virginia. This area had previously experienced a 2.5 magnitude earthquake in  
9 2000 prior to these events. Braxton County is located on the eastern edge of the Marcellus  
10 shale play and drilling in this area began in 2006. In March 2009, a nearby Class II disposal well  
11 began injecting Marcellus oil and gas production wastewater into the Marcellus formation.

12 The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas  
13 standard permit application package incorporated site assessment, well construction and  
14 completion information along with other supporting documentation to demonstrate the  
15 protection of USDWs. The permit application contained detailed geologic information, such as  
16 an isopach and structure map. Site assessment documentation included surface maps, location  
17 plats, disposal depths and inventory of offset wells within the area of review. Well construction  
18 details provided to the state included well specifics (casing, cement information, perforations,  
19 and completion information) and disposal conditions (interval, rate, and pressure requested). A  
20 step rate test was also included with the permit information. In addition, an annual report filed  
21 by the operator provides monthly injection volumes and pressure data. WG review of the  
22 annual injection reports indicated that the well operated within the permitted pressure limits.  
23 The data reported by the operator indicated that the well did not operate continuously.

24 In response to the seismic activity, the WVDEP reduced the maximum injection rate in  
25 September 2010. No additional earthquakes were recorded in the area since this restriction  
26 was enacted until January 2012. In response to the 2012 event, the WVDEP reduced the  
27 monthly disposal volume by half the permitted value and is currently researching the geologic  
28 structure of the area. The WVDEP and the WG found no conclusive evidence linking the cause  
29 of the seismicity to the disposal well.

30 In February 2012, WVDEP began requiring UIC permit applications to provide detailed geologic  
31 information specifically to identify subsurface faults, fractures or potential seismically active  
32 features. This includes at a minimum, public or privately available geologic information such as  
33 seismic survey lines, well records, published academic reports, government reports or  
34 publications, earthquake history, geologic maps, or other like information to access the



potential that injection of fluids could lead to activation of fault features and increasing the likelihood of earthquakes. More details on this case study are available in Appendix F.

### YOUNGSTOWN, OHIO

Since March 17, 2011, a series of low magnitude earthquakes occurred in Mahoning County in and around Youngstown, Ohio. Historically, there had been no prior seismicity in the area. Commercial disposal operations started in December of 2010 in Mahoning County located on the eastern edge of Ohio. Earthquake activity was located within a mile of the Northstar 1 commercial disposal well.

The Ohio Department of Natural Resources (ODNR) standard permit application package incorporated some site data and well construction and completion information along with other supporting documentation to demonstrate the protection of USDWs. Site documentation reviewed by the WG included surface maps, location plats, disposal depths and inventory of offset wells within the area of review. Well construction details provided to the state included well specifics (casing, cement information, perforations, and completion information) and disposal conditions (interval, rate, and pressure requested). A step rate test was also included with the permit information. In addition, an annual report filed by the operator provides injection volumes and pressure data. WG review of the annual injection reports indicated that the well operated within the permitted pressure limits.

On December 31, 2011, Youngstown experienced a 4.3 magnitude earthquake (ANSS) resulting in the disposal well being immediately shut-in. Based on a Pennsylvania Geological Survey report, the only known deep-seated fault appears to be about 20 miles away from the seismic activity. Further details on this case study are available in Appendix G.

According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* published in March 2012 by the ODNR, data suggests seismicity was related to Class II disposal. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The ODNR report also suggests that pressure from disposal activities may have communicated with a stressed fault located in the Precambrian basement rock. The ODNR will prohibit Class II injection into the Precambrian basement rock and has proposed additional standard permit requirements to facilitate better site assessment and collection of more comprehensive well information. The proposed supplemental permit application documentation will include more geologic data, comprehensive well logs, a plan of action should seismicity occur, a step-rate test, a determination of the initial bottomhole pressure, and a series of operational controls: continuous pressure monitoring system, an

automatic shut-off system, and an electronic data recording system for tracking fluids. ODNR is also considering purchasing seismometers to bolster earthquake monitoring capabilities.

### COMMON CHARACTERISTICS AND LESSONS LEARNED FROM CASE STUDIES

There are common aspects for wells suspected of inducing seismicity from the case studies summarized in this report. Some approaches to minimize and manage injection-induced seismicity can involve a trial and error process, such as disposal rate control. Other aspects and approaches include:

- Initiating dialog with operator can provide early voluntary action from operators, including well shut-in, or acquisition of site data. Initiating dialogue between the operator and UIC regulator resulted in the voluntarily shut in of some suspect disposal wells. For example, an operator showed a proprietary 3-D seismic interpretation to the permitting authority, revealing a deep seated fault. (North Texas, Central Arkansas)
- While existing operational data can provide insight into the reservoir behavior of the disposal zone, the quality can be greatly improved by requesting a falloff test or increased recording of operational parameters. For example, fractured flow behavior was confirmed from the falloff test analyses for the Ellenburger disposal zone (North Texas), while increased frequency of permit parameters improved the operational analysis from multiple wells. (Central Arkansas)
- Location of a disposal zone near or into the basement rock may have provided hydraulic access of pressure buildup or disposal fluids to area basement faults. Site data in Central Arkansas and Ohio suggest direct communication with basement rocks or faults communicating with basement rocks. Therefore, regional geologic site assessments may be warranted or existing assessments expanded to evaluate deeper faults, fault trends, and historic seismicity. Published sources may provide regional deep-seated fault information. (all case study areas)
  - Injection into fractured disposal zones overlying basement rock may be vulnerable to injection-induced seismicity. (all case study areas)
- Engaging external seismographic expertise may bring a more accurate location of the active fault, through reinterpretation or increased seismic monitoring. This is especially true when earthquake event magnitudes increased over time. (Central Arkansas, Ohio and West Virginia) In both North Texas and Central Arkansas, participation by state geological survey or university researchers resulted in expert consultation, installation of additional seismometers, and a clearer understanding of the deep seated active faulting.
- Operational analysis of disposal rates and pressures exhibited enhanced injectivity responses in some wells, possibly representative of injection-induced fracturing,

- 1 extension of existing fractures, or lower permeability formations accepting fluids at  
2 higher pressure within the disposal zone. (all case study areas)
- 3 • Director discretionary authority was used to acquire additional site information, request  
4 action from operators, and prohibit disposal operations. Specific examples include:
    - 5 ○ Increased monitoring and reporting requirements for disposal well operators  
6 provided additional operational data for reservoir analysis in Central Arkansas.
    - 7 ○ Required one Central Arkansas well to include a seismic monitoring array prior to  
8 disposal as an initial permit condition.
    - 9 ○ Plugged or temporarily shut-in suspect disposal wells linked to injection-induced  
10 seismicity while investigating or interpreting additional data (all case study areas).
    - 11 ○ Defined a moratorium area in Central Arkansas prohibiting Class II disposal wells in  
12 defined high risk area of seismic activity.
    - 13 ○ Decreased allowable injection rates and total monthly volumes in response to  
14 seismic activity in West Virginia.
  - 15 • Operating wells below fracture pressure prevents or minimizes fracture propagation. This  
16 may require actual testing, such as a step rate test, to measure the formation parting  
17 pressure or conducting an operational analysis for indication of enhanced injectivity.
  - 18 • Increased seismic monitoring stations may be warranted in many areas to pinpoint active  
19 fault locations and increase detection of smaller events. Additional stations installed in the  
20 DFW airport area of North Texas and Central Arkansas resulted in reliable identification of  
21 active fault locations. In West Virginia, epicenters of recorded events are scattered, due to  
22 insufficient stations in proximity to the activity.
  - 23 • A combination of approaches may be needed to minimize and manage induced seismicity at  
24 a given location. (all case study areas)
  - 25 • The magnitude of the earthquakes in some cases showed general increases over time.  
26 (Central Arkansas, Ohio and Virginia)

## 27 RESERVOIR ENGINEERING APPLICATIONS

28 Another aspect of the project included application of reservoir engineering techniques.  
29 Reservoir engineering methodologies provide core tools for evaluating key components of  
30 injection-induced seismicity as part of the site assessment process. The three key components  
31 behind injection-induced seismicity are the presence of a stressed fault, pressure buildup from  
32 disposal activities, and a pathway for the increased pressure to communicate from the disposal  
33 well to the fault. Reservoir engineering tools provide important details about the specific site  
34 assessment by quantifying reservoir conditions and by characterizing the flow pathways that  
35 impact the amount and distribution of pressure buildup from disposal operations.  
36 Characterizing flow pathways helps determine if pressure buildup is being dispersed radially or

1 in a preferential direction. The reservoir transmissibility of the pathway impacts the amount of  
2 pressure buildup from disposal activities. More specifics on these reservoir engineering  
3 applications are included in Appendix C.

#### 4 RESERVOIR ENGINEERING ASPECTS OF SITE CHARACTERIZATION

5 Aspects of site characterization take place both prior to and after initiation of disposal.  
6 Reservoir engineering concepts, if applied during the site characterization, would provide  
7 important insights for induced seismicity investigations. However, application of these  
8 concepts may require collecting additional information during the site assessment review of the  
9 disposal well. Unless specifically requested by the UIC Director, the data are not submitted as  
10 part of the typical permit application process.

#### 11 RESERVOIR PATHWAYS

12 Reservoir characteristics are often identified by production/flow related evidence, drilling  
13 evidence, geological evidence, or geophysical indications of fractures (Narr et al., 2006).  
14 Production performance is not applicable in most disposal well applications.

15 Stratigraphic formations used as disposal zones can have a complex range of porosity types and  
16 permeability values. For example, a naturally fractured formation typically has two types of  
17 porosity, fracture porosity and matrix porosity. For this report, matrix porosity refers to the  
18 pore spaces in rocks from depositional or chemical changes. Fractures in rocks create a second  
19 type of porosity and form permeable avenues for fluid flow. If the matrix pore spaces are not  
20 interconnected, then matrix permeability is low and the resulting pressure buildup from  
21 disposal operations would be higher. The nature of fracture and matrix porosities and  
22 permeabilities within the disposal zone is a critical aspect of pressure buildup from injection,  
23 and is therefore important for induced seismicity evaluation.

24 Radial flow models, generally used in the UIC program, assume homogeneous rock properties  
25 throughout the disposal zone. Disposal zones that are non-homogeneous in nature, such as  
26 naturally fractured reservoirs, may not be suitable for radial flow model applications. Naturally  
27 fractured reservoirs are characterized by fractures and the bulk rock, referred to as the matrix.  
28 Pressure response to disposal in a naturally fractured reservoir is dependent on the number,  
29 size and width of the natural fractures, and also the degree of communication with the matrix  
30 properties (Cinco-Ley, 1996; Kamal, 2009). In cases where the natural fractures communicate  
31 effectively with the porous matrix, the reservoir response remains similar to that of a radially  
32 homogenous formation. If the matrix rock does not have adequate porosity and permeability;  
33 the natural fractures provide the majority of the storage capacity of the reservoir. Therefore,  
34 the pressure may not readily dissipate into the matrix, may increase more rapidly than a

homogeneous reservoir, and may be transmitted greater distances through the natural fractures.

Pressure transient well testing, such as a falloff test, can identify reservoir flow characteristics and provide information on the completion condition of the disposal well. Falloff tests may also indicate the presence of a nearby sealing fault or boundary. Step rate tests, another type of pressure transient test, measure the formation parting pressure of the reservoir which may be used to set operational surface pressure limitations. In North Texas, falloff tests conducted in one disposal well indicated a naturally fractured reservoir that was characteristic of the Ellenburger disposal zone. The WG reviewed step rate tests conducted in West Virginia and Ohio with surface pressure measurements and noted that slope breaks were observed during both tests, however data quality was marginal.

#### PRESSURE BUILDUP

Pressure buildup from disposal activities and the areal distribution of the pressure increase in the injection zone represent key issues to consider during site characterization as both relate to the potential for injection-induced seismicity. Injection reservoirs with favorable hydraulic characteristics distribute pore pressures more effectively, resulting in lower pressure buildup, and are therefore more desirable for reducing the potential of induced earthquakes (Nicholson and Wesson, 1990).

An initial static bottomhole pressure measurement is an essential data point for determining if the reservoir is underpressured or normally pressured prior to initiating disposal activities. The initial bottomhole pressure measurement also provides the starting point for determining the amount of pressure buildup in the reservoir over time. Static bottomhole pressure measurements are typically performed as either a single downhole measurement with the injector shut-in, or obtained at the end of a falloff test.

The maximum amount of pressure buildup predicted from disposal operations and the lateral extent of the pressure influence are influenced by the flow characteristics of the reservoir. The area of review determination for Class II disposal wells in the federal UIC regulations includes options for the calculation of the pressure buildup using radial flow equations or alternately using a fixed quarter mile radius from the disposal well without calculations (40 CFR §146.6). Depending on reservoir flow characteristics, the pressure influence from the disposal activity may extend beyond a quarter mile radius of the well and use of the radial flow equations in the regulations may not be applicable for calculating the zone of endangering pressure influence. For example, pressure from a disposal well operating in a naturally fractured reservoir exhibiting linear flow characteristics would not dissipate radially, or in all directions, away from

the well. Consequently, pressure distribution in a naturally fractured reservoir would not be uniform around the well but the higher pressures would be directionally focused. A disposal zone that does not exhibit homogeneous reservoir radial flow characteristics may be a site assessment consideration or issue with respect to evaluating pressure buildup and the potential induced seismicity.

## RESERVOIR ENGINEERING APPROACHES

Reservoir engineering approaches may be applicable for addressing site characterization issues. An operational approach to site characterization may consist of plotting readily available disposal well injection pressure and rate data reported to UIC Directors as part of the Class II permitting process. Operational data analysis can involve plotting bottomhole pressure (BHP) gradients or a cumulative injection pressure behavior function, such as the Hall integral (Hall, 1963; Izgec and Kabir, 2009; Jarrell and Stein, 1991). Operational data analysis provides a qualitative look at the reservoir.

For ongoing issues identified during the site evaluation, reservoir engineering approaches using available Class II disposal well operational data submitted to UIC Directors may be useful. For example, if fracturing was a concern, a Hall integral plot may be prepared from the reported injection rates and pressures to look for signs of enhanced injectivity during operations. The Hall integral is an operational assessment of injection rates and pressures based on a steady state flow analysis. Steady state flow analysis is useful for identifying changes in operating conditions, such as the fracturing of the formation or opening of less permeable formations within the disposal zone as pressures increase. Reservoir operational analysis may also indicate if pressure is being dispersed radially from the disposal well.

Monitoring approaches may also be used to address issues identified in the site characterization. As previously discussed, pressure transient tests, such as falloff and step rate tests provide a more quantitative description of reservoir conditions. Pressure testing may be used to identify changes in flow characteristics over time. Periodic static bottomhole pressure measurements can monitor pressure increases in the reservoir for the prevention of endangerment to USDWs. Annular pressure tests and production logging can confirm well mechanical integrity if this is a concern following area seismic activity. Production logs, such as temperature surveys or radioactive tracer surveys may be used to monitor the portion of the disposal zone accepting injected fluids in disposal zones containing heterogeneous formations or multiple formations.

## 1 DECISION MODEL

2 The primary objective of the WG was to develop a practical tool to consider in minimizing and  
3 managing injection-induced seismicity in new or existing Class II disposal wells. The decision  
4 model was designed to identify if the three key components of injection-induced seismicity are  
5 present. The WG developed a decision model that incorporates a site assessment  
6 consideration process addressing the varying reservoir characteristics related to the three key  
7 components. The decision model provides the UIC Director flexibility through a combination of  
8 site assessment considerations and approaches to identify and address seismicity criteria for  
9 both existing and new disposal wells. Site-specific information can be applied to determine  
10 which considerations listed in the decision model reveal possible issues. No one single question  
11 addresses the considerations needed to evaluate a new or existing disposal well. If issues are  
12 identified, the decision model discusses operational, monitoring, and management approaches  
13 that can be used to address the issues.

14 [Figure 1](#) includes a diagram of the decision model, and is followed by a discussion relating to  
15 the range of considerations for site assessment. Issues identified through the site assessment  
16 consideration thought process are then addressed, as needed, by a combination of operational,  
17 monitoring, and management approaches. These options were identified by the WG from  
18 reservoir engineering methods, literature reviews, analyses of the case studies, and  
19 consultations with researchers, operators, and state regulators. A more detailed discussion of  
20 the decision model is included in Appendix B.

## 21 SITE ASSESSMENT CONSIDERATIONS

22 Site assessment considerations identify and evaluate specific site characteristics that may  
23 represent potential issues for injection-induced seismicity. The three key components behind  
24 injection-induced seismicity are the presence of a stressed fault, pressure buildup from disposal  
25 activities, and a pathway for the increased pressure to communicate from the disposal well to  
26 the fault (Nicholson and Wesson, 1990). Uncertainties about any one of the three components  
27 may warrant collection or review of additional data within the site assessment consideration  
28 process.

29 Site assessment considerations may include aspects from both geoscience and petroleum  
30 engineering. The site assessment considerations in the decision model were designed to  
31 identify issues relating to any of the three key components. Details about the decision model  
32 diagram and its associated site assessment considerations are provided in [Appendix B](#).

33 Site assessment considerations determined relevant for the decision model were the following:

- 1 • Is there a demonstrated history of successful disposal activity?
- 2 • Have there been regional area seismic events?
- 3 • Is the area geoscience information sufficient to assess the likelihood of faults and
- 4 seismic events?
- 5 • Are the available data sufficient to characterize reservoir pathways?
- 6 • Is there adequate information to characterize the potential pressure buildup?
- 7 • Is consultation with external geoscience or engineering experts warranted?
- 8 • Is additional site or regional information warranted?

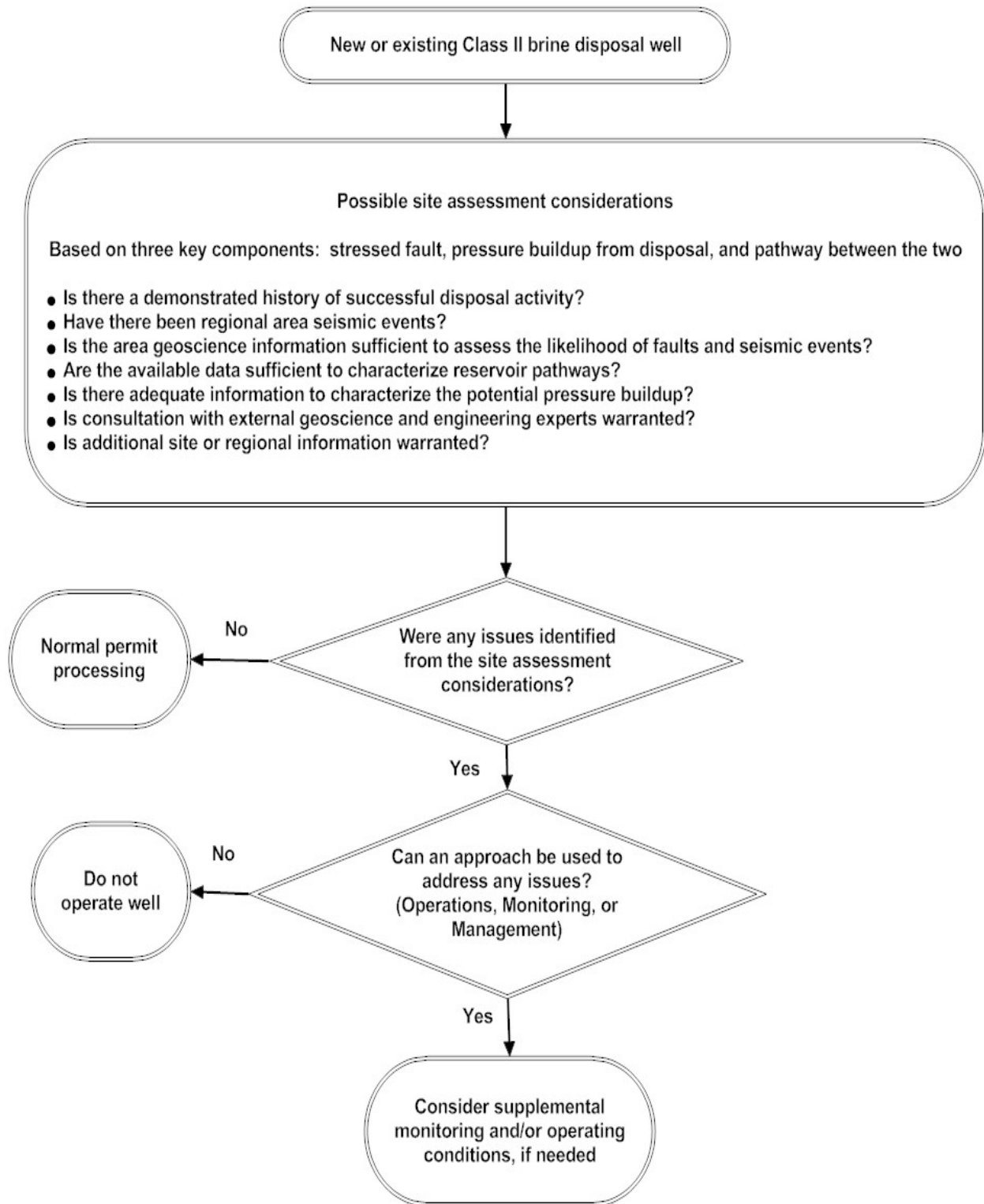
9 Below are three different scenarios. Different site assessment considerations may be  
10 applicable to each scenario.

- 11 1) An existing disposal well operating in a zone with historical injection and lack of
- 12 historical seismicity,
- 13 2) An existing disposal well in an area not experiencing seismicity, and requests a
- 14 substantial increase to injection volumes or pressure, or
- 15 3) A new disposal well in a disposal zone or area where little or no disposal activity has
- 16 previously occurred.

17 Scenario 1) may not warrant further site assessment based on successful historical operations,  
18 while scenarios 2) or 3) may warrant additional site characterization consideration, especially if  
19 the well was located in a tectonically stressed region.



1 FIGURE 1: INJECTION-INDUCED SEISMICITY DECISION MODEL



2

## APPROACHES FOR ADDRESSING SITE ASSESSMENT ISSUES

There are a number of approaches available to manage and minimize significant seismic events. These can be broadly categorized as operational, monitoring and management approaches. An operational approach may include, for example, restricting the maximum allowable injection rate or pressure. A monitoring approach may necessitate collection of additional monitoring data, for example, operational pressures, additional seismic monitoring, or well testing. A management approach covers agency, operator and public interaction. The Director determines which, if any, approaches are important depending on site-specific considerations. Details about the approaches for addressing issues associated with the site assessment considerations are provided in Appendix B.

## COMPARISON OF DATA COLLECTED UNDER EXISTING CLASS II DISPOSAL WELL REGULATIONS TO RELEVANT INDUCED SEISMICITY DATA

Class II UIC programs do not specifically require information to assess potential induced seismicity. Director discretionary authority can be used, however, to require data prior to permitting or additional monitoring of an existing well if determined necessary for protection of USDWs. Frequently, well operators collect more comprehensive data with greater frequency than UIC Directors require for reporting. Regulators who invest in frequent communications with operators may have the opportunity to further refine information for an area and minimize the likelihood of induced seismicity. For example, larger oil and gas operators have recommended the relocation of a proposed disposal well located near a large fault identified by internal geoscience information.<sup>12</sup>

Class II disposal well sites are evaluated for the protection of USDWs. Depending on program requirements, regional or area geologic data may be included with the permit applications, illustrating known faulting. Well tests may be included in a permit application for a specific purpose, such as step rate tests to measure fracture pressure or falloff tests to identify flow characteristics, measure static reservoir pressure, or assess well completion condition. An Initial bottomhole pressure measurement may be included to determine if the disposal zone is normally pressured, under pressured, or over pressured. The depth of the disposal zone, well construction and completion information, included with the permit application, are also useful data when evaluating induced seismicity.

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<sup>12</sup> During the NAS question and answer session of the September 2011 meeting in Dallas, on Induced Seismicity Potential in Energy Technologies, oil and gas operators mentioned they will directly communicate with a smaller operator and suggest relocation of a disposal well or protest a disposal well location during the permit process if internal company information suggests the proposed well is located near a large fault.

A permit application typically includes an evaluation of other well penetrations within the ¼ mile area of review of the disposal well to ensure that the penetration(s) will not serve as vertical conduits or provide a potential for USDW endangerment. Other data to characterize or describe the disposal zone may also be collected depending on the regulatory agency policy. For example, in the West Virginia case study, a step rate test was conducted on the well and submitted with the permit application along with a geologic map in addition to an evaluation of wells within a ¼ mile area of review.

Class II disposal permits are also typically issued with some frequency of injection pressure and rate data reporting requirement as part of permit compliance. There is typically a maximum allowable injection pressure limitation. Review of injection rate and pressure data assist in correlating injection well behavior with area seismicity. For example, pressure responses from disposal activities may change as a result of seismic activity. In the Arkansas case study area, bihourly reporting of operating injection pressures and volumes was required following area seismic activity.

## RESEARCH NEEDS

The WG did not exhaust all avenues with respect to research on the value of petroleum engineering approaches. An abundance of research describing seismology and geomechanical behavior in the form of physical rock properties exists although studies that combined petroleum engineering and geoscience approaches could not be found by the WG. The WG recommends future practical research using a multidisciplinary approach and a holistic assessment addressing disposal well and reservoir behavior; geology; and area seismicity. Such an approach would benefit from combined expertise in geology, petroleum engineering, geophysics and seismology, which may not be available through one entity. For example, areas of expertise should include, but may not be limited to structural and stratigraphic geology; rock mechanics; seismology; reservoir characterization; reservoir fluid flow mechanisms; and disposal well construction, completion and performance.

The WG employed Hall plots for the reservoir engineering analysis because regulators may perform the analysis using widely available spreadsheet software; however, other approaches exist, such as the Reciprocal Productivity Index that may be applicable if inverted to injection conditions. WG recommends a practically applied research project focused on assessment of injection well operating data to determine if there is a correlation between operating well behavior and seismicity. One of the key outcomes of the project would be a practical set of methodologies to assess operating data (templates) using injection well operating data acquired for existing UIC permits.

There is also a need for research related to geologic siting criteria for disposal zones for areas with limited or no existing data. The geologic and geophysical study could focus on stratigraphic horizons that could serve as disposal zones in these areas, the nature of subsurface stresses in basement rocks of these areas, and a more detailed regional geological assessment of basement faults. If sufficient earthquake catalog data are available, additional research to devise a statistical approach to relate Class II disposal wells operating parameters with induced seismicity would be useful.

## REPORT FINDINGS AND OBSERVATIONS

Three key components behind injection-induced seismicity are the presence of a stressed fault, pressure buildup from disposal activities, and a pathway for the increased pressure to communicate from the disposal well to the fault. Understanding the geologic characteristics of a site is therefore essential to evaluating the potential for injection-induced seismicity.

Unconventional resources and new technologies have resulted in the need for disposal wells in areas with few or no existing wells. Uncertainties in site geology and reservoir characteristics may exist in areas with limited to no historic drilling or exploration operations.

An absence of historical seismic events in the vicinity of a disposal well does not provide assurance that induced seismicity will not occur; however, this absence may be a supportive indicator of induced seismicity if events occur following activation of an injection well. Proof of induced seismicity is difficult to achieve, but is not a prerequisite for prudent action to further assess the possibility of induced seismicity by acquiring more data. Some events started at a lower magnitude and showed a general increase over time, such as in the Arkansas, Ohio and West Virginia case studies.

There are common factors related to wells suspected of inducing seismicity, both from the literature and recent examples:

- The magnitude of the earthquakes in some cases showed general increases over time.
- Deep disposal wells were in direct communication or suspected to be in hydraulic communication with basement rocks and stressed faults as in the Arkansas and Ohio case study examples.
- Disposal commonly occurred into disposal zones with naturally fractured reservoir characteristics as in the Arkansas and North Texas case study examples.
- Operational analysis of injection rates and pressures exhibited enhanced injectivity responses, possibly representative of injection-induced fracturing, extension of existing

fractures, or lower permeability formations accepting fluids at higher pressure within the disposal zone. Enhanced injectivity was observed in all the case study areas.

Though rare, hydraulic fracturing (HF) induced seismicity is possible if the HF encounters a stressed fault.

The accuracy of measurements of seismic events is dependent on the quantity and location of seismometers (Daley et al., 2010; Eager et al., 2006; Grasso and Wittlinger, 1990). A regional view of seismic history may give an indication of subsurface stresses in an area that has no local seismic history. Subsequent reviews of seismic surveys in two of the cases (DFW North Texas, and Arkansas) identified nearby deep faults as the source of the seismic activity. In the Arkansas case study area, there is a history of clustered seismic events approximately 9 miles to the southeast.

In the case studies, the UIC Directors took action through discretionary authority to manage and minimize seismic events. The WG also found no indication that the injection wells associated with the case study areas injected outside of the operational boundaries or designated injection zones established by the permit parameters.

Basic petroleum reservoir engineering practices coupled with geoscience information can provide a better understanding of reservoir and fault characteristics (Lee et al., 2003; Kamal, 2009). The reservoir engineering analysis of operational data identified anomalies in some case study wells, which could have warranted additional site assessment or monitoring. The WG noted that published research was generally narrowly directed and lacked a multidisciplinary approach of how disposal wells and induced seismicity interrelate.

There are a variety of human activities, which are documented in the literature, that have induced seismicity (Davis and Frohlich, 1993; Nicholson and Wesson, 1990; Suckale, 2009, 2010; Coplin and Galloway, 2007). Seismicity requires the presence of a stressed fault (Ahmad and Smith, 1988; Majer et al., 2011; Nicholson and Wesson, 1990; Nicholson and Wesson, 1992). Significant seismic events induced by HF have not been documented in the literature reviewed for this report. HF generally induces microseismic magnitude ( $<1.0$ ) events (Maxwell, 2011; Phillips et al., 2002; Warpinski, 2009) although HF into a stressed fault has produced seismicity up to magnitude 2.8 (de Pater and Baisch, 2011; Holland, 2011).

In naturally fractured reservoirs, assessment of primary storage capacity (fractures and/or matrix) and its impact on pressure buildup is critical in determining if the zone is a viable disposal zone. The areal extent of pressure buildup from disposal activities is controlled by injection rates and reservoir characteristics of the injection interval (Kamal, 2009; Lee et al.,

2003). Measurement of the initial bottomhole pressure prior to disposal indicates if the disposal zone is normally pressured or under pressured. Under-pressured reservoirs may have a larger differential of pressure buildup prior to inducing seismicity. Pressure buildup associated with Class II brine disposal wells can be transmitted over extended distances from the wellbore.

Operational and monitoring practices for managing and minimizing injection-induced seismicity that were used or proposed in the scientific literature and case examples in this report include:

- Reduced injection rates: This approach is likely a trial and error process, starting at lower rates and increasing gradually
- Increased monitoring frequency of injection parameters such as formation pressure and rates
- Intermittent injection operations to allow time for pressure dissipation, with the amount of shut-in time needed being site-specific
- Use of multiple injection wells separated by some distance to more widely dissipate subsurface pressures
- Operating wells below fracture pressure to prevent or minimize fracture propagation. This may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity
- Installation of seismic monitoring instruments in areas of concern to allow more accurate location determination and increased sensitivity for seismic event magnitude.

## RECOMMENDATIONS TO MINIMIZE OR MANAGE INJECTION-INDUCED SEISMICITY

The WG found no single recommendation addresses all the complexities related to managing or minimizing injection-induced seismicity. Recommendations included in this report were derived from a combination of WG expertise, case studies, consultations with outside experts, and data from literature reviews. These can be divided into three technical categories (site assessment, well operational, and monitoring) and a management component. The first step in the induced seismicity evaluation process is to conduct a site assessment. Based on the site assessment, further operational and monitoring approaches may be warranted.

### SITE ASSESSMENT

- Use the decision model site assessment considerations for determining if the well site may need additional requirements to ensure protection of USDWs. These include:
  - Assess past disposal history for correlation with area seismicity.
  - Evaluate regional and local seismicity to identify active subsurface stresses.

- Evaluate regional and local area geoscience information to assess the likelihood of activating faults and causing seismic events.
- Review the available data to characterize reservoir pathways which could allow pressure communication from disposal activities to a stressed fault.
- Assess the pressure buildup potential by evaluating the storage capacity of disposal formations prior to use, especially those with low porosity and permeability.
- Consult with external geoscience or engineering experts as needed to acquire or evaluate additional site information.
- Consider collecting additional site assessment information in areas with no previous disposal activity and limited geoscience data or reservoir characterization prior to authorizing disposal.
- Request more geoscience and reservoir engineering information, as needed to minimize injection-induced seismicity, to reliably assess reservoir behavior during injection. Many reservoir engineering considerations for site characterization are not part of the typical permit application process.
- Determine the primary storage capacity (fractures and/or matrix) of naturally fractured reservoirs to assess the impact on pressure buildup and determine if the zone is a viable disposal zone.
- Measure the initial bottomhole pressure prior to disposal to determine if the disposal zone is normally or under-pressured. Under-pressured reservoirs may have a larger differential of pressure buildup from Class II disposal injection prior to inducing seismicity.
- Conduct geologic evaluations for purposes of assessing induced seismicity potential and consider the tectonic and geologic history with an expanded area of evaluation for earthquake history and fault trends.

## WELL OPERATIONS

- Conduct a reservoir engineering analysis of operational data on wells in areas where seismicity has occurred. Basic reservoir engineering practices coupled with geoscience information can provide a characterization of the flow behavior in the injection zone, quantify reservoir conditions and delineate fault characteristics.
- Conduct pressure transient testing in disposal wells suspected of causing seismic events to obtain information about injection zone characteristics near the well.
- Modify injection well permit operational parameters as needed to minimize or manage seismicity issues. For example:

- Reduced injection rates: This approach is likely a trial and error process, starting at lower rates and increasing gradually.
- Inject intermittently to allow time for pressure dissipation, with the amount of shut-in time needed being site-specific.
- Separate multiple injection wells by a larger distance for pressure distribution since pressure buildup effects in the subsurface are additive.
- Contingency measures in the event seismicity occurs.
- Operate wells below fracture pressure to maintain the integrity of the disposal zone and confining layers. This may require actual testing, such as a step rate test, to measure the formation parting pressure or conducting an operational analysis for indication of enhanced injectivity.

## MONITORING

- Require additional seismometers as needed for increased accuracy of seismic information. The accurate measurement of seismic events depends on the quantity and location of seismometers.
- Increase monitoring frequency of injection parameters, such as formation pressure and rates, to increase the accuracy of analysis.
- Increase monitoring of fluid specific gravities in commercial disposal wells with disposal fluids of variable density since the density impacts the bottomhole pressure in the well.

## MANAGEMENT

Several proactive practices were identified for managing or minimizing injection-induced seismicity.

- Take earlier action to minimize the possibility of injection-induced seismicity rather than requiring substantial proof.
- Engage the operators early in the process, especially in areas that are determined to be vulnerable to injection-induced seismicity. Based on the Arkansas, Ohio, and West Virginia case studies, some events start at a lower magnitude and increase over time.
- Provide training for UIC Directors on new reservoir operational analysis techniques to understand the spreadsheet parameters.
- Employ a multidisciplinary team for practical research to address the links between disposal well and reservoir behavior; geology; and area seismicity.
- Engage external multidisciplinary experts from other agencies or institutions. For example, engineers may engage geophysicists to interpret or refine data from seismic events for accuracy and stress direction.



- Develop public education programs to explain some of the complexities of injection-induced seismicity.

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## 1 GLOSSARY OF ACRONYMS AND TERMS

### 2 ACRONYMS

|    |       |  |
|----|-------|--|
| 3  | AAPG  | American Association of Petroleum Geologists                               |
| 4  | ANSS  | USGS Advanced National Seismic System                                      |
| 5  | AOGC  | Arkansas Oil and Gas Commission  |
| 6  | BHP   | Bottomhole Pressure  |
| 7  | CERI  | Center for Earthquake Research and Information                             |
| 8  | EPA   | US Environmental Protection Agency   |
| 9  | HF    | Hydraulic Fracturing   |
| 10 | GIA   | Geothermal Implementing Agreement  |
| 11 | IEA   | International Energy Agency  |
| 12 | MMbls | Million barrels  |
| 13 | NCEER | Central and Eastern United States, CERI Earthquake database                |
| 14 | NEIC  | National Earthquake Information Center, US Geological Survey               |
| 15 | NTW   | National Technical Workgroup   |
| 16 | PDE   | Preliminary Determination Earthquake, NEIC Earthquake database             |
| 17 | RRC   | Railroad Commission of Texas   |
| 18 | SMU   | Southern Methodist University  |
| 19 | SPE   | Society of Petroleum Engineers   |
| 20 | SRA   | Eastern, Central & Mountain States NEIC Earthquake database                |
| 21 | UIC   | Underground Injection Control  |
| 22 | USDW  | Underground Sources of Drinking Water                                      |
| 23 | USGS  | US Geological Survey   |
| 24 | USHIS | Significant US quakes, NEIC Earthquake database                            |
| 25 | WG    | Injection-induced Seismicity Working Group                                 |
| 26 | WVDEP | West Virginia Department of Environmental Protection Office of Oil and Gas |

### 27 TERMS

28 Catalog aka earthquake catalog from USGS online Earthquake Search of the NEIC PDE catalog of  
29 earthquakes. <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>

Class II injection wells inject fluids (1) which are brought to the surface in connection with conventional oil or natural gas production and may be commingled with waste waters from gas plants which are an integral part of production operations, unless those waters are classified as a hazardous waste at the time of injection, (2) for enhanced recovery of oil or natural gas; and (3) for storage of hydrocarbons which are liquid at standard temperature and pressure (40 CFR 146.5(b)).

Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS). Earthquakes resulting from human activities will be called induced earthquakes in this report.

Epicenter is the point on the earth's surface vertically above the hypocenter (or focus) point in the crust where a seismic rupture begins. NEIC coordinates are given in the WGS84 reference frame. The position uncertainty of the hypocenter location varies from about 100 m horizontally and 300 m vertically for the best located events, those in the middle of densely spaced seismograph networks, to tens of kilometers for global events in many parts of the world.

Isopach is a contour map illustrating the variations of thickness of defined stratum.

Magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on the measurement of the maximum motion recorded by a seismograph or the energy released. Generally, damage is reported for magnitudes above 5<sup>13</sup>. Magnitude will refer to the numbers reported by USGS or the NEIC, not separated between moment, body wave, or surface wave magnitudes.

| Magnitude <sup>14</sup> | Earthquake Effects  |
|-------------------------|---|
| 2.5 or less             | Usually not felt, but can be recorded by seismograph.                 |
| 2.5 to 5.4              | Often felt, but only causes minor damage.                             |
| 5.5 to 6.0              | Slight damage to buildings and other structures.                      |
| 6.1 to 6.9              | May cause a lot of damage in very populated areas.                    |
| 7.0 to 7.9              | Major earthquake. Serious damage.                                     |
| 8.0 or greater          | Great earthquake. Can totally destroy communities near the epicenter. |

Microseismicity has no formal definition, but generally is an earthquake with a magnitude less than 2. (*The Severity of an Earthquake*, USGS website:  
<http://earthquake.usgs.gov/learn/topics/richter.php>)

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<sup>13</sup> Building damage was reported following 2011 earthquakes near Trinidad, Colorado (5.3) and near Greenbrier, Arkansas (4.7).

<sup>14</sup> (Michigan Tech, 2011)

- 1 Step rate test consists of a series of increasing injection rates as a series of rate steps and
- 2 estimates the pressure necessary to fracture the formation.
- 3 Stressed fault for this report denotes a fault with the potential to cause a significant
- 4 earthquake.
- 5 Tectonic is the rock structure and external forms resulting from the deformation of the earth's
- 6 crust. (Dictionary of Geological Terms, 1976)
- 7

DRAFT

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DRAFT



## **APPENDIX A: UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC #2011-3**

### **UIC NATIONAL TECHNICAL WORKGROUP PROJECT TOPIC: #2011- 3**

#### **Technical Recommendations to Address the Risk of Class II Disposal Induced Seismicity**

##### **Background**

Recent reports of injection-induced seismicity have served as a reminder that the UIC Program can and should implement requirements to protect against significant seismic events that could ultimately result in USDW contamination. The UIC Program's Class I hazardous and Class VI siting provisions require rigorous evaluations for seismicity risks. The other well classes, in contrast, allow the UIC Director the flexibility to decide if and when such evaluations are needed. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to inform and enhance strategies for avoiding significant seismicity events related to Class II disposal wells.

##### **Project Objectives**

The UIC NTW will analyze existing technical reports, data and other relevant information on case studies, site characterization and reservoir behavior to answer the following questions:

1. What parameters are most relevant to screen for injection induced seismicity? Which siting, operating, or other technical parameters are collected under current regulations? (Geologic siting criteria, locations and depths of area pressure sources and sinks, injection rates and pressures, cumulative injection or withdrawals of an area, evaluation of fracture pressure, stresses or Poisson's ratio, etc.)
2. What measurement tools or databases are available that may screen existing or proposed Class II disposal well sites for possible injection induced seismic activity? What other information would be useful for enhancing a decision making model? (Flow chart incorporating seismicity/hazard database resources, reservoir testing methods, area faulting, measuring or recording devices, reservoir pressure transient models, seismic models, other screening tools, etc)
3. What screening or monitoring approaches are considered the most practical and feasible for evaluating significant injection induced seismicity?
4. What lessons have been learned from evaluating case histories?
  - a. Did reviews of injection rate and pressure data sets reveal any concerns?
  - b. Were any pressure transient tests conducted?
  - c. How were the seismicity events attributed to Class II disposal activities?
  - d. What levels of site characterization information were available?
  - e. Which UIC regulations have regulators used to address the situation?
  - f. Were there areas of concern identified that existing UIC regulations did not address?
  - g. Any other lessons learned?

## **Output**

The end-product of this analysis should be a report containing technical recommendations for avoiding significant levels of injection induced seismicity that EPA can share with UIC Directors. The UIC NTW will produce a report that includes the following elements:

1. Comparison of parameters identified as most applicable to induced seismicity with the technical parameters collected under current regulations
2. Prepare a decision making model – conceptual flow chart
  - a. Provide strategies for preventing or addressing significant induced seismicity
  - b. Identify readily available applicable databases or other information
  - c. Develop site characterization check list
  - d. Explore applicability of pressure transient testing and/or pressure monitoring techniques
3. Summary of lessons learned from case studies
4. Recommended measurement or monitoring techniques for higher risk areas
5. Applicability of conclusions to other well classes
6. Define if specific areas of research are needed

## **Milestones**

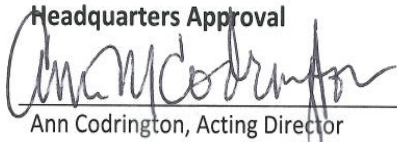
- July 2011 – Authorization from UIC managers for UIC NTW to proceed with injection induced seismic project proposal. Assemble UIC NTW project team and assign tasks to project members. Collect and distribute, to UIC NTW project team, information from published studies, peer-reviewed articles, and State and Federal UIC programs.
- August 2011 – Create project sub-teams. Collect and evaluate information from case histories. Review compilation of information and develop technical recommendations for addressing risks of significant injection induced seismicity. Create project teams.
- September 2011 - Consolidate input from project sub-teams
- October 2011 – Prepare and present preliminary technical recommendations and report to UIC NTW membership. Finalize technical recommendations and report with input from UIC NTW membership.
- November 2011 – Submit report for presentation to UIC management
- December 2011 – Finalize report and post to public accessible UIC NTW website

## **Project Focus Group**

Phil Dellinger (R6; Lead); Leslie Cronkhite (HQ; HQ-Lead); Jill Dean (HQ); Bob Smith (HQ); David Albright (R9); Sarah Roberts (R8); Tom Tomastik (Ohio Department of Natural Resources); Steve Platt (R3); Dave Rectenwald (R3), Susie McKenzie (R6), Brian Graves (R6), Ken Johnson (R6), Nancy Dorsey (R6), state representatives associated with case histories.

**Target Delivery Date:** December 2011

**Headquarters Approval**



Ann Codrington, Acting Director  
Drinking Water Protection Division  
Office of Ground Water and Drinking Water

7/20/11

Date

**SPECIFIC GUIDANCE TO WORKGROUP:** (space unlimited)

DRAFT

## APPENDIX B: DECISION MODEL

|  |     |
|--|-----|
| Site Assessment Considerations .....   | B-1 |
| • Is there demonstrated history of successful disposal activity? .....                                       | B-2 |
| • Have there been regional area seismic events? .....  | B-2 |
| • Is the area geoscience information sufficient to assess the likelihood of faults and seismic events? ..... | B-3 |
| • Are the available data sufficient to characterize reservoir pathways? .....                                | B-4 |
| • Is there adequate information to characterize potential reservoir pressure buildup? .....                  | B-5 |
| • Is consultation with external geoscience or engineering experts warranted? .....                           | B-6 |
| • Is additional site or regional information warranted? .....  | B-7 |
| Approaches to Address Site Assessment Issues .....   | B-7 |
| Operational Approaches .....   | B-7 |
| Monitoring Approaches .....  | B-7 |
| Management Approaches .....  | B-9 |
| References .....   | B-9 |

An objective of the report was to develop a practical tool for the evaluation of injection-induced seismicity. Because of the variations in geology and reservoir characteristics, the WG selected a thought process to consider while evaluating site-specific data from the Class II disposal well area. The process summarizes the various considerations and approaches identified by the WG from reservoir engineering methods, literature reviews, analysis of the case studies, and consultations with researchers, operators, and state regulators. The decision model is included as Figure 1 in the report.

With few exceptions, injection-induced seismicity occurs in response to increased pore pressure from injection, transmitted through a pathway, to a stressed fault plane (Nicholson and Wesson, 1992). Therefore, the WG identified three broad categories to consider when evaluating an existing or proposed Class II disposal well potential for injection-induced seismicity. These three categories are: site assessment considerations, and operational and monitoring approaches. The Director determines which considerations are important depending on site-specific circumstances. Site assessment considerations are intended to guide which operational, monitoring, and management approaches are appropriate to address induced seismicity issues. The Director also ascertains what, if any, additional site assessment information or monitoring may be necessary for the protection of USDWs.

### *SITE ASSESSMENT CONSIDERATIONS*

No one single question addresses all the site assessment considerations needed to evaluate a new or existing disposal well. These considerations focus on the three key components behind injection-induced seismicity -- the presence of a stressed fault, pressure buildup from disposal

activities, and a pathway for the increased pressure to communicate from the disposal well to the fault. The considerations included in the decision model are discussed individually below, along with the positive and negative aspects for each.

• IS THERE DEMONSTRATED HISTORY OF SUCCESSFUL DISPOSAL ACTIVITY?

The absence of historical seismic events in the vicinity provides no guarantee there will be no future seismic events. Wells that have a successful history of disposal of oil and gas related wastes are less of a consideration. However, areas with a long history of disposal activity and no corresponding seismic events may require additional evaluation if substantial changes in disposal volumes or pressures are requested. A disposal well located in an area with no previous disposal activity may also require additional evaluation. Uncertainties in reservoir characterization may exist in these new areas with few or no existing wells, possibly justifying the need for additional site characterization information and analysis.

• HAVE THERE BEEN REGIONAL AREA SEISMIC EVENTS?

The absence of historical seismic events in the local vicinity of an injection well may not provide assurance that induced seismicity will not occur; however, this absence is a supportive indicator of induced seismicity if seismic events occur following injection. A more regional view of seismic history may give an indication of subsurface stresses in an area that has no local seismic history. For example, there is a history of clustered seismic events approximately nine miles to the southeast of the Arkansas case study area although the immediate vicinity had no history of seismic activity.

Two factors should be considered when evaluating the seismic history<sup>15</sup>-- the size of the seismic history search area around the well in question, and the level and frequency of seismic activity in that area that would justify additional site characterization. In the determination of the size of the search area, consideration should be given to the accuracy of the recorded seismic events. This is dependent on the frequency and proximity of seismometers in the area. For instance, a tight seismometer grid (6 mile spacing) can provide a location accuracy of about 0.6 miles, while the accuracy with a station spacing of 125 miles is around twelve miles<sup>16</sup>. The permanent monitor grid spacing in most of the Continental U.S. area is approximately 200 miles. As the continental western margin, Alaska and Hawaii are tectonically active (measurable fault movement and/or volcanic activity), the seismometer spacing is tighter,

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<sup>15</sup> <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/> search choices

<sup>16</sup> Information is taken from the USGS Task 1 draft response, discussed later in this report.

1 resulting in more accurate event locations. Appendix L discusses the various earthquake  
2 database locations in greater depth.

3 There are a number of complexities in determining if the seismic history warrants a more in  
4 depth analysis or additional site characterization information. Accurate seismic history and  
5 event location may be difficult to obtain due to variability in seismometer density. Additionally,  
6 small earthquakes may be a precursor to larger ones. All of the case study locations in this  
7 report had a lack of seismic history in the local vicinity of the disposal wells prior to injection. In  
8 each case, small, felt events followed injection. In Arkansas, the activity increased in frequency  
9 and magnitude over the course of 18 months (see Appendix E, Table E-1), and caused some  
10 minor building damage. The induced seismic events at the Arkansas site occurred as a result of  
11 pressure build-up from injection operations causing a previously unidentified fault to slip.

12 An apparent increase in seismicity may be a result of additional station deployment.  
13 Deployment information can be viewed or downloaded from the IRIS website:  
14 <http://www.usarray.org/maps>. This website includes information on stations in the rolling two-  
15 year EarthScope array as well as the permanent station locations. Seismometers may be  
16 loaned for temporary recordings such as the North Texas DFW airport and Cleburne, or  
17 Greenbrier, Arkansas seismic events.

18 • IS THE AREA GEOSCIENCE INFORMATION SUFFICIENT TO ASSESS THE LIKELIHOOD OF FAULTS AND SEISMIC  
19 EVENTS?

20 With few exceptions, injection-induced earthquakes occur in response to increased pore  
21 pressure from injection, transmitted through a pathway to a stressed fault plane.  
22 Understanding the area geology through available geoscience information may clarify two of  
23 these induced seismicity components: the nature of the pathway transmitting the pore  
24 pressure response and identification of faults subject to the pressure response. The lateral  
25 continuity and heterogeneity of the disposal zone influence both the pressure buildup from  
26 disposal operations and the distribution pathway. The effectiveness of overlying and  
27 underlying confining zones may influence the vertical pressure dispersion.

28 Accurate fault assessment, as part of the overall site characterization, is a critical aspect of  
29 managing injection-induced seismicity (Nicholson and Wesson, 1990). Subsurface faults exist  
30 throughout most of the country; however, the presence of a fault itself may not be a concern.  
31 If a site is in an area with a history of seismic activity, stressed faults are likely present in the  
32 region. Consideration should be given to the possibility of deep seated faulting, as reported  
33 with the Rocky Mountain Arsenal (Hsieh and Bredehoeft, 1981) and Central Arkansas induced  
34 events (Ausbrooks, 2011a, 2011b, 2011c, 2011d; Horton and Ausbrooks, 2011).

1 There are a number of possible options for determining the presence or absence of faulting  
2 around a proposed or existing disposal well including reviewing published literature, state  
3 geological agency reports, commercial structure maps or evaluating any available seismic  
4 surveys. While the latter are the most definitive, they are also the most expensive, time  
5 consuming to acquire, and may require access to land that cannot be readily obtained. Well  
6 operators may have exploration seismic surveys to enhance fault analysis for the site  
7 characterization. For example, active faults in Arkansas and the DFW area were identified first  
8 from seismic activity, and then verified on the operator's interpreted 3D seismic surveys,  
9 (Chesapeake Energy, personal communication, September 16, 2011). If seismic data are  
10 available, a reanalysis of seismic data may help identify any deep seated faults, and if present,  
11 the extent of the fault or associated fractures, although some faults, such as those that are  
12 near-vertical, may be missed. Correlations of logs or review of cross-sections may indicate  
13 missing sections or fault cuts. If a fault is present, information on the origin, throw, and vertical  
14 extent of the fault may be a consideration. Logs may also identify the rock characteristic of the  
15 disposal zone and the reservoir pathways the pressure from disposal operations may  
16 encounter. If site-specific geoscience information is limited or insufficient and regional studies  
17 indicate faults or subsurface stress in the broader area, additional information may be needed  
18 to evaluate the likelihood of inducing seismicity.

19 Geologic site characterization information on flow characteristics, fracture networks and stress  
20 directions may be available from: 1) regional and local geologic studies, or 2) information from  
21 well logs, core analysis, and hydraulic fracturing results. Any published articles discussing the  
22 basin, reservoir rock or structural history of the area, may indicate if faulting, fracturing, or  
23 directional flow is present.

24 • ARE THE AVAILABLE DATA SUFFICIENT TO CHARACTERIZE RESERVOIR PATHWAYS?

25 The potential pathway or the ability of the reservoir to transmit pressure to a stressed fault is  
26 best characterized by combination of geoscience and petroleum engineering information.  
27 Geologic information can help characterize the nature and continuity of the disposal zone. For  
28 example, a geologic isopach map or cross-section, may define the lateral continuity of the  
29 disposal zone and the area potentially impacted by the pressure response from disposal  
30 operations. Evaluation of the confining capability of formations overlying and underlying the  
31 disposal zone may indicate the potential for vertical pressure dispersal outside the disposal  
32 zone. A type log from the disposal well or area offset well may illustrate if confining layers are  
33 present. Other useful aspects for consideration include the number of formations and  
34 thickness of permeable strata included within the disposal zone. Heterogeneities in the  
35 receiving formations will impact the pathway for pressure distribution away from the disposal

1 well. This level of detailed information, while useful, is not typically required for Class II  
2 disposal well operations and therefore may not be available in all situations.

3 Review of daily drilling reports and openhole logs may suggest characteristics of the disposal  
4 zone and overlying confining zones, helping to describe the reservoir pathway. For example,  
5 borehole washouts or elongated boreholes observed on a caliper log may suggest a higher  
6 stressed or fractured zone. Heavier mud weights used while drilling may suggest the presence  
7 of higher pressure zones. Core data are not typically acquired during the drilling of Class II  
8 disposal wells, but if available, could show natural fractures (open or sealed), karstic rock or  
9 fault gouging if present. Openhole logs, such as a fracture finder log, multi-arm dipmeter,  
10 borehole televiwer, or variable-density log may also indicate fractured zones. The depth of  
11 the disposal zone to the basement rock may be a consideration if the disposal well location is  
12 identified as an area with high stressed fault potential.

13 Production logging data in an existing well may supplement geologic data by providing  
14 additional insight about out of interval fluid movement and vertical pressure dispersal.  
15 Production logs such as radioactive tracer surveys, temperature logs, noise logs, flowmeters  
16 and oxygen activation logs can show where fluid exits the wellbore and provide quantitative  
17 values for fluid volumes being emplaced into the intervals identified. Wellbore fill, at the base  
18 of a well, may reduce the interval thickness, alter the injection profile, and increase the  
19 pressure buildup during disposal operations. For example, wellbore fill may cover a large  
20 portion of the disposal zone in a well with a short perforated interval; resulting in a greater  
21 pressure buildup within the thinner interval receiving fluid. Production logs can also indicate if  
22 fluid is channeling upward or downward behind the casing to other intervals for potential  
23 hydraulic impact and show intervals impacted by cumulative long term injection.

24 Reservoir engineering approaches, such as a reservoir falloff test, can also provide clues about  
25 the pressure transmission pathway, by indicating whether the injection zone is behaving in a  
26 linear (possibly fractured) or homogeneous (non-fractured) manner. Falloff testing is not a  
27 requirement for Class II wells, but has been used as a lower cost alternative in some Class II  
28 operations to characterize the disposal reservoir flow parameters, reservoir pressure buildup,  
29 and well completion condition. Falloff testing is associated with the petroleum reservoir  
30 engineering approach which is discussed in further detail in Appendix C.

31 • IS THERE ADEQUATE INFORMATION TO CHARACTERIZE POTENTIAL RESERVOIR PRESSURE BUILDUP?

32 Reservoir pressure buildup, a key component of induced seismicity, is influenced by both the  
33 flow behavior and hydraulic characteristics of the disposal zone. Pressure buildup calculations  
34 can be performed if reliable estimates of reservoir flow parameters are available and the



1 reservoir is assumed to have homogeneous radial flow behavior. However, many disposal  
2 formations have heterogeneous properties. For example, several cases of suspected injection-  
3 induced earthquakes in the literature appear to be characterized by injection zones located  
4 within fractured formations (Belayneh et al, 2007; Healy et al, 1968; Horton and Ausbrooks,  
5 2011). For these reservoirs, a fixed quarter mile area of review or the conventional pressure  
6 buildup equations used to calculate the zone of endangering influence may not be applicable.

7 To perform conventional reservoir pressure buildup calculations, knowledge of disposal zone  
8 hydraulic characteristics is required. Disposal zone hydraulic characteristics include static  
9 reservoir pressure, permeability, effective net thickness, porosity, fluid viscosity, and system  
10 compressibility. Details about these characteristics are generally determined from some  
11 combination of pressure transient testing results, logging and completion data, and fluid and  
12 rock property correlations. Once these values are obtained, pressure buildup calculations can  
13 then be performed to access the magnitude of pressure increases throughout the disposal  
14 reservoir. In many Class II disposal applications, limited reservoir property measurements are  
15 available and actual pressure buildup calculations are done using assumed or accepted area  
16 formation characteristic values.

17 Actual reservoir falloff tests can provide clarity as to whether the homogeneous reservoir  
18 behavior assumption is valid or pressure buildup projections should be calculated using a  
19 different set of fluid flow behavior assumptions. Naturally fractured disposal formations  
20 involving induced seismicity would likely require more complex pressure buildup prediction  
21 methods to account for non-radial reservoir behavior. A static bottom hole pressure  
22 measurement, typically obtained at the end of a falloff, also provides an assessment of  
23 reservoir pressure increase around the injection well, offering insight into the magnitude of  
24 pressure buildup that an area fault may have been subjected to.

- 25 • IS CONSULTATION WITH EXTERNAL GEOSCIENCE OR ENGINEERING EXPERTS WARRANTED?

26 Consulting with seismologists at either state or federal geological surveys can provide  
27 additional information and may be necessary in situations, where warranted, based on existing  
28 site specific conditions. For example, in the Arkansas case study, the UIC Program coordinated  
29 with researchers from Memphis University and Arkansas Geological Survey to successfully  
30 acquire critical information on ongoing low level seismic activity. Data from this effort formed  
31 the basis for a disposal well moratorium in the area of disposal induced seismicity. Seismic  
32 history for any area in the U.S. is readily available on the USGS website and/or state geological  
33 agencies at no cost (see Appendix L). However, if there is sufficient information, seismologists  
34 can refine the event locations and depths. This could identify fault locations. Other expertise  
35 may be available through academia, other agencies, or consultants.

- IS ADDITIONAL SITE OR REGIONAL INFORMATION WARRANTED?

Based on review of the available site characterization information, additional information may be needed based on the unique site-specific circumstances.

#### *APPROACHES TO ADDRESS SITE ASSESSMENT ISSUES*

In cases where issues are identified from site assessment considerations, the operational, monitoring, and management approaches outlined below provide options for managing or minimizing injection-induced seismicity. If no issues were identified during the site assessment process, the UIC Director may continue normal permit processing. If site assessment issues cannot be addressed, an alternative disposal option may be needed.

#### *OPERATIONAL APPROACHES*

Reduced injection rates and volumes have been used in a number of cases where suspected induced seismicity was occurring. The action is immediate, and easy to implement and track. Reduction in the injection rate lowers the pressure buildup in the disposal zone and may provide an alternative to shutting in the well. Intermittent periods of disposal could provide shut-in time for pressure buildup to dissipate between operational periods. The characteristic of the reservoir pathway will impact how much the pressure will decrease during the shut-in period. There would be no direct cost to implement, though the reduced disposal volume could impact facility operations and wastewater management.

More frequent operational data collection may also be needed to properly assess site specific situations relevant to induced seismicity. More accurate data may require electronic measuring equipment to record and store data which may add cost. In the Arkansas case study, bi-hourly monitoring of injection pressure and volume providing additional operational data points to evaluate well responses and also provided more data for the operational analysis of the data.

Pressure buildup in the reservoir is additive, so if multiple wells are needed to manage waste, expanding the area between the disposal wells completed in the same disposal zone would result in less pressure buildup in areas where the pressure responses overlap. Spreading the distance between wells may allow higher injection rates at each well. Higher costs would likely be associated with drilling multiple wells and transferring wastewater to the wells.

#### *MONITORING APPROACHES*

Additional monitoring may be useful in cases where the site characterization does not provide adequate certainty with respect to the possibility of induced seismicity. Reservoir parameters such as static reservoir pressure provide an indication of the pressure buildup in the formation

1 over time. A static reservoir pressure is easy and inexpensive to obtain, however it requires the  
2 well be shut-in for a period of time prior to the measurement. A shut-in pressure may also be  
3 obtained at the end of a falloff test period.

4 Additional monitoring through more frequent operational data collection may indentify  
5 changes in well behavior during the operation of the well if analyzed, e.g., using a Hall Plot. In  
6 Arkansas, bi-hourly monitoring of injection pressure and volume provided additional data  
7 points in graphs and operational data analyses. Operational analysis uses the injection rates  
8 and pressures routinely collected by the UIC Director. The analysis can be conducted using a  
9 spreadsheet and does not require specialized software, but interpretation of the data may  
10 require specialized expertise. The frequency of data collection can influence the accuracy of  
11 the analysis.

12 Monitoring for seismic events using the existing seismic network may provide an early warning  
13 of seismic activity, if continuously observed. For example, in Arkansas, additional monitoring  
14 stations were deployed to provide increased accuracy and resolution level of seismic events.  
15 Therefore, additional seismicity monitoring and reporting may be a prudent monitoring  
16 approach for areas deemed to have a higher likelihood of induced seismicity. The monitoring  
17 could use the existing USGS seismic monitoring network or include seismometers installed in  
18 response to the injection operation. Additional seismometers would result in more accurate  
19 locations of seismic events and greater sensitivity to detect smaller events. Additional seismic  
20 monitoring stations and data analysis requires geophysical expertise to process and review. As  
21 demonstrated in Arkansas, additional monitoring stations were added and provided increased  
22 accuracy and resolution level of seismic events leading to identification of a basement fault.

23 Contingency plans, e.g., based on a seismic threshold, could be established in advance and used  
24 in conjunction with this monitoring to assure expedited response actions by the injection well  
25 operator in response to seismic events. Monitoring and reporting under an existing seismic  
26 array is inexpensive but data accuracy may be limited.

27 Periodic pressure transient testing, e.g., a falloff test provides valuable information about  
28 reservoir characteristics and well completion condition. The test requires the alternative  
29 handling of wastewater during the shut-in period of the well for the test. Analysis of data  
30 typically requires some specialized software and technical expertise to evaluate the results.

31 Step rate tests may be conducted to confirm or in lieu of the calculated fracture gradient. The  
32 test typically requires a pump truck and access to additional fluid volumes for continuous  
33 injection during the test. An operating pressure gradient can be calculated from existing  
34 injection rate and pressure data, and compared to the fracture gradient determined from the  
35 step rate test to confirm the well is operating below the fracture pressure gradient. Additional

1 cost of continuously recording the pressure and rate data allows confirmation of pressure  
2 stabilization during each rate step and better fracture gradient analysis by allowing each rate  
3 step to be analyzed as an injectivity test.

4 Running production logs, such as a flowmeter, radioactive tracer survey, or temperature log, to  
5 profile the formation receiving fluids may be another monitoring technique for evaluating fluid  
6 emplacement trends. The thickness of the interval receiving fluid can impact the amount of  
7 pressure buildup in the reservoir. An alternative handling of wastewater during the shut-in  
8 period may be needed.

## 9 MANAGEMENT APPROACHES

10 Management approaches address agency, operator and public interaction. These approaches  
11 provide proactive practices for managing or minimizing injection-induced seismicity. Proactive  
12 approaches could include taking earlier action to minimize the possibility of injection-induced  
13 seismicity rather than requiring substantial proof. For example, in the Arkansas, Ohio, and  
14 West Virginia case studies, some events started at a lower magnitude and increase over time.  
15 Engaging the operators early in the process, especially in areas that are determined to be  
16 vulnerable to injection-induced seismicity could be another approach. Other approaches may  
17 consist of providing training, employing multidisciplinary expert and research teams, and  
18 developing public education programs to explain some of the complexities of injection-induced  
19 seismicity.

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## APPENDIX C: PETROLEUM ENGINEERING CONSIDERATIONS

|   |      |
|---|------|
| What are petroleum engineering considerations?.....                                       | C-1  |
| Petroleum Operations Engineering Approach.....  | C-2  |
| Reservoir Engineering Approach .....  | C-3  |
| What Types of Reservoir Engineering-Applicable Data are available? .....                  | C-4  |
| Reservoir Engineering Analysis of Operational Data .....                                  | C-5  |
| Operational Data Plots and Analyses:.....   | C-6  |
| Reservoir engineering analysis of Pressure Transient data.....                            | C-14 |
| Pressure Transient Test Plots and Analysis Approach:.....                                 | C-16 |
| Specific Aspects of Pressure Transient Tests Commonly Associated with Disposal Wells..... | C-22 |
| Falloff Test.....   | C-22 |
| Step Rate Tests.....  | C-22 |
| Step Rate Injectivity Test Plot .....   | C-25 |
| How can the operational data and pressure transient test analyses be used? .....          | C-26 |
| How did the WG perform the case study evaluations?.....                                   | C-27 |
| References .....  | C-28 |

Petroleum engineering methods and approaches offer many ways of assessing injection-induced seismicity by analyzing currently available data. This appendix discusses the petroleum engineering analyses and tests that were used for this project, including how the case studies data were analyzed and the applicability of these petroleum engineering approaches for assessing potential induced seismicity concerns. Other reservoir engineering methods or applications may also be useful to operators and UIC Director in evaluating injection-induced seismicity. Collectively, these techniques may assist in a site-appropriate evaluation of potential injection-induced seismicity.

### *WHAT ARE PETROLEUM ENGINEERING CONSIDERATIONS?*

Site assessment considerations in the decision model focus on three key components for the occurrence of injection-induced seismicity: a stressed fault, disposal interval pressure buildup from injection and a reservoir flow pathway to transmit the pressure buildup from the disposal well to the fault. Petroleum engineering methods address both pressure buildup and the type of reservoir flow pathway present around the disposal well as well as characterizing reservoir behavior during the well's operation. Under limited circumstances, petroleum engineering approaches may also provide area fault information. These methodologies can provide both quantitative and qualitative descriptions of the disposal wellbore and reservoir conditions.

Petroleum engineering methods address various well aspects including well construction, well completion, well operations, and reservoir characterization to evaluate and optimize well performance. In this report, these fundamental petroleum engineering methods were applied

to evaluate disposal wells in the four case study areas using available data. The WG assessment is subdivided into operational and reservoir behavior compared to seismic event activity.

### *PETROLEUM OPERATIONS ENGINEERING APPROACH*

The operational engineering approach focuses on disposal wellbore conditions and how these parameters might contribute to injection-induced seismicity. Well construction and completion conditions, the well's injection profile (where the injected brine is emplaced), and injection rate determine bottomhole injection pressure conditions, and impact the zonal isolation of the injected fluids. Applications of these aspects are detailed below.

UIC Class II disposal permits typically include disposal well construction and completion data such as well completion date, casing and tubular dimensions and depths, cementing records, total well depth, packer depth and type, waste brine density, completion interval(s) and type (e.g., openhole, screen and gravel pack, or perforations), and initial pressure prior to disposal. Detailed knowledge of the well layout is necessary for assessing the isolation of the disposal zone through casing cementing, geological confining layers, location of the disposal zone relative to basement rock, and if the disposal zone includes multiple intervals or is focused on a single interval.

Knowledge of the brine density and wellbore tubular dimensions coupled with the injection rate enables calculation of an injecting bottomhole pressure by accounting for the hydrostatic pressure of the brine column and friction pressure loss of the tubing. This calculation is particularly useful for converting surface pressure injection history to estimated bottomhole conditions. The operational bottomhole pressure gradient trend can be compared against the estimated or measured fracture gradient for the disposal zone to assess if injection-induced fracturing is a concern. Static bottomhole pressures can be estimated from the static fluid level and brine density.

Cased hole and production logs can also provide useful wellbore condition information to assess injection operation conditions. Cased hole logs such as a cement bond log can identify good or poorly cemented portions of the injection casing along with the uncemented intervals. Production logs (radioactive tracer surveys, flowmeters, temperature, oxygen activation, and noise logs) provide important information about injection profiles, zonal isolation, and upward and downward fluid channeling. The wellbore injection profile shows where fluid is going into the formation, which in turn controls the reservoir pressure buildup response.

Temperature logs typically require the well be shut-in for 36 to 48 hours prior to running the log so the temperature differential between the injected fluid and reservoir temperature can be effectively measured. Radioactive tracer tests use slug chases or velocity shots to evaluate the

1 injection profile in the well. The radioactive ejector tool has limited capacity and may require  
2 multiple trips in and out of the well to reload the ejector tool when profiling large disposal  
3 zones. Flowmeters, such as a spinner survey, are typically less effective in large diameter casing  
4 or openhole intervals. Production logs are routinely used for Class I hazardous waste injection  
5 wells, but are not typically required for Class II disposal wells. Several of the case study wells  
6 had long vertical openhole completions, but no assessment of the injection profile. In the Ohio  
7 case study, a production log was conducted to assess the portion of the disposal zone receiving  
8 fluid.

9 UIC operational compliance case history data generally included monthly injection volumes  
10 with maximum and/or average surface injection pressures. Using this data, the WG assessed  
11 well construction conditions and calculated estimated operating bottomhole injection  
12 pressures for each case study well. The calculated bottomhole operating pressures for each  
13 case history well were then used in the reservoir engineering approach analyses.

#### 14 *RESERVOIR ENGINEERING APPROACH*

15 Reservoir engineering is an area of petroleum engineering focusing on the behavior and  
16 performance of reservoirs. While reservoir engineering typically focuses on oil and gas  
17 production well performance, its techniques and methodologies also readily extend to  
18 analyzing injection well behavior. The reservoir engineering approach couples reservoir rock  
19 and fluid properties with time, pressure, and injection rate data from well operations for  
20 building models to describe and predict reservoir behavior.

21 The reservoir engineering approach was incorporated into the case study analyses. Analysis of  
22 disposal well operating data and well testing, such as pressure transient tests, can provide  
23 critical details about the injection interval reservoir pathway and the completion condition of  
24 the well. Completion conditions reflect conditions at or near the wellbore while reservoir  
25 characteristics describe the injection interval away from the well. For example, a well that has  
26 been fracture stimulated will display a different response than an unfractured well. Reservoir  
27 characteristics identify the type of disposal zone reservoir pathway present and indicate its  
28 tendency to dissipate pressure buildup, either radially or in a preferential direction.

29 Reservoir characterization is a crucial component in assessing injection formation flow patterns,  
30 the formation's capacity to transfer pressure responses, and the completion condition of a  
31 disposal well. Identifying anomalous reservoir behavior through analyses and then correlating  
32 the results with geoscience data may suggest relationships between injection well pressure  
33 response and induced seismic activity.



## WHAT TYPES OF RESERVOIR ENGINEERING-APPLICABLE DATA ARE AVAILABLE?

The most common data available for Class II disposal wells are injection rates/volumes and injection tubing pressures, these are routinely reported as part of both EPA direct implementation and state UIC Class II program requirements. Bottomhole pressures (BHP), more suitable for evaluating reservoir conditions, are not as readily available. The timeframe for reporting varies between regulatory agencies and depends on site circumstances.

This report focused on reservoir engineering analyses of available operational data sets to evaluate well and reservoir behavior, and the site geologic environment. Although less common, some pressure transient test data were available and included in the report. The following data types are generally available for Class II disposal wells:

### Common UIC monitoring data reported:

- Injection rates or volumes
- Surface tubing pressures

### Common data in UIC permit applications:

- Well construction
  - Tubing dimensions and depth
  - Casing dimensions and depths
  - Cementing information
  - Completion interval
  - Type of completion
- Reservoir information
  - Gross and net injection zone thickness
  - Porosity
  - Name and description of relevant (disposal zone and overlying confining zones) geologic formations
  - Bottomhole temperature
  - Initial static BHP
- Reservoir and injection fluids
  - Specific gravity
  - Fluid analysis

### Planned pressure test measurements and resulting data:

- Falloff/injectivity test: reservoir characterization and well completion condition

- Step rate test: fracture gradient
- Static pressures: initial pressure and pressure change during well operations

### RESERVOIR ENGINEERING ANALYSIS OF OPERATIONAL DATA

Injection volumes and tubing pressures are regularly collected as part of both EPA direct implementation and state UIC Class II program requirements. Graphs of injection volume and operational pressures reflect reservoir behavior over time. Longer periods of operational data (typically in months or years) results in a deeper, though less refined look into the reservoir than a shorter timeframe pressure transient test. An analogy to the operating data graph would be to have a continuously recording stationary astronomical telescope that sees deeper and deeper into space the longer it records in the same direction.

As operating data was more prevalent than pressure transient data, the WG focused on reservoir engineering analysis of these data sets to relate them back to reservoir behavior and geologic environment. Both operating data and pressure transient data shown on appropriate plots represent “pictures” of mathematical responses that can be fit to reservoir models which qualitatively and, in some cases, quantitatively characterize well completion and performance conditions, reservoir flow geometry, and, in limited cases, reservoir geology. Hence, the data can be used to “describe” the reservoir pathway.

Graphical format for the reservoir engineering analytical plots varies, ranging from tandem linear axes to dual log axes depending on the type of analysis performed. The graphs may display certain patterns or quantitative values which inform the reservoir analyst as to what type of reservoir flow characteristics are present or identifies changes in reservoir behavior over time.

Operational data are analyzed using the steady state radial flow equation, in the form of the Hall integral and its derivative, while pressure transient tests are analyzed using solutions to the radial diffusivity equation. Operational data includes both injection rate and pressure information, but actual data reported can vary depending on the regulatory agency requirements. For example, injection volumes may be reported daily, monthly, or quarterly. Injection pressures may be reported as a maximum value and monthly average or monthly minimum and maximum values.

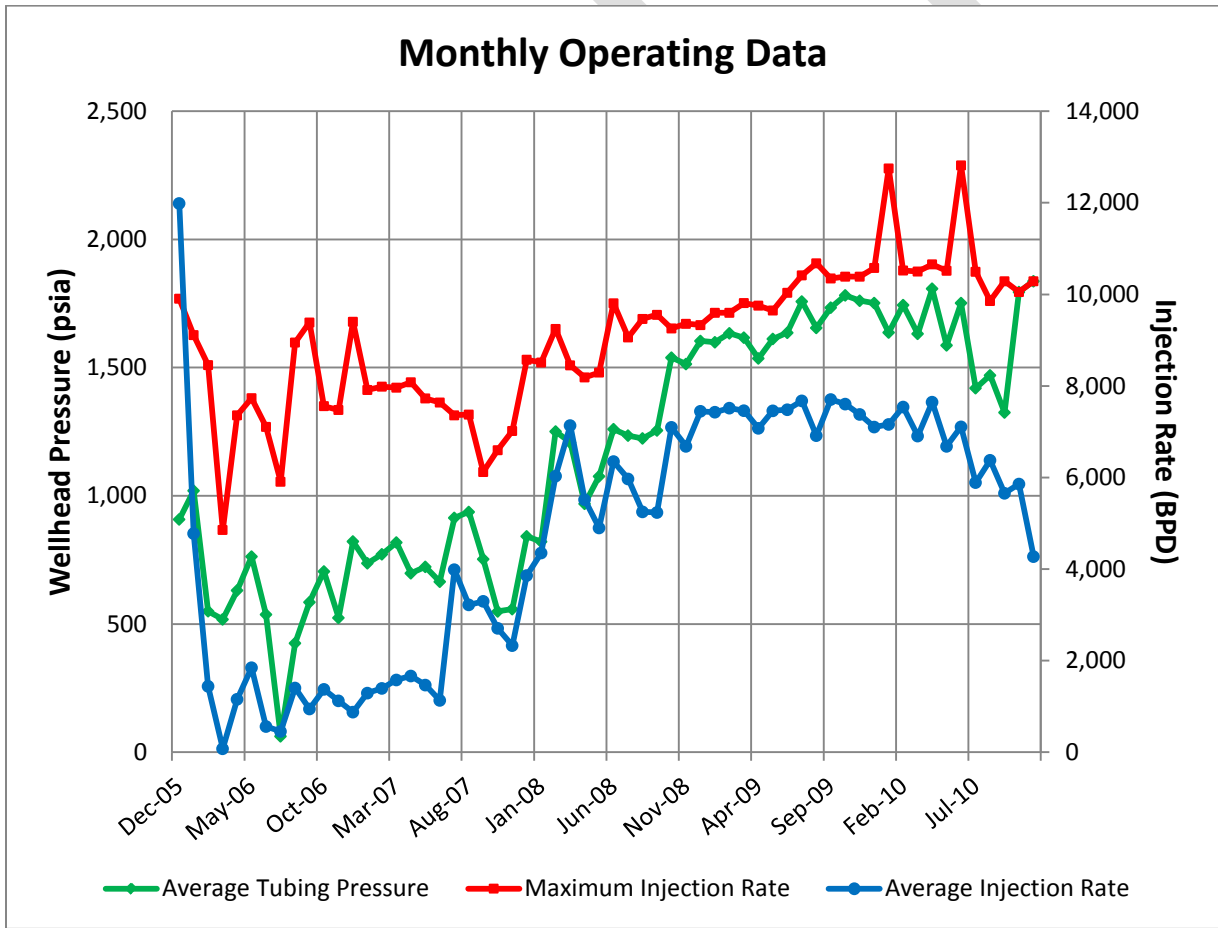
For best applicability, surface pressures should be converted to bottomhole conditions, prior to performing a Hall plot analysis. This conversion requires the analyst account for friction pressure loss with a correlation, such as Hazen-Williams (Westaway and Loomis, 1977; Lee and Lin, 1999), based on the tubing specifications information and injection rates. The hydrostatic pressure from the brine column must be added to the surface pressure as part of the

bottomhole pressure calculation. The frequency of injection rates can also impact the quality of the analysis. Plots, calculations, and analyses associated with operational data are summarized below:

**OPERATIONAL DATA PLOTS AND ANALYSES:**

- Overview surface pressure and rate/volume plot (Figure C-1)
  - Cartesian (linear) plot of surface injection pressure and rate/volume versus date
    - y-axis: pressure and rate/volume
    - x-axis: date
  - Identifies trends or large changes in pressure and/or injection rate/volume behavior
  - Provides a timeline of operational activity
  - Challenges: Frequency of data reported, intermittent well use, quality of data

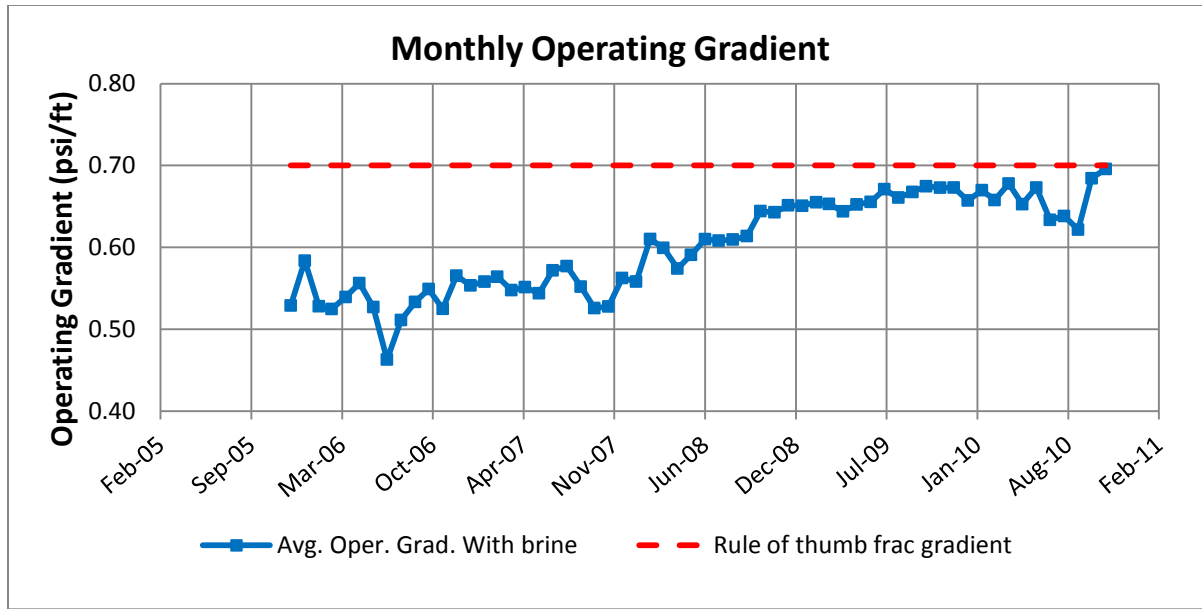
**FIGURE C-1: OVERVIEW PLOT OF MONTHLY OPERATING TUBING PRESSURES AND INJECTION RATE**



- Operating bottomhole pressure gradient plot (Figure C-2)
  - Cartesian plot of bottomhole operating pressure gradient versus date

- Y-axis: operating pressure gradient
- X-axis: date
- Pressure gradient is BHP divided by depth (psi/ft)
  - Compare operating pressure gradient to fracture pressure gradient
  - If operating above fracture gradient, new or extension of fractures may be occurring
  - Area specific fracture gradients are more appropriate, if calculated or measured
    - A 0.7 rule of thumb fracture gradient was used for this report
- Estimation of bottomhole injection pressure
  - Add hydrostatic column based on brine specific gravity to the surface tubing pressure and subtract friction pressure loss
    - Calculate hydrostatic pressure of the fluid column:
      - (disposal brine specific gravity) x (fresh water gradient) x (depth)
      - Brine specific gravity from fluid analysis or estimate
    - Friction loss estimated using tubing dimensions and Hazen-Williams friction loss correlation (Lee, et.al., 1999; Westaway, et.al., 1977)
      - Tubing friction factor, C, is based on tubing type
  - BHP calculated at depth
    - Case study calculations based on tubing seat
- Challenges:
  - Conversion of surface pressure to BHP requires estimation of friction pressure and hydrostatic column of fluid
    - Varying injectate specific gravity introduces uncertainties in calculation of the hydrostatic fluid column
    - Frequency of rates data impact friction calculations
    - Tubing specifications are needed to estimate the appropriate friction factor, C
  - Frequency and type of data reported may require manipulation to get equivalent timeframes for both injection rates and pressures

1 **FIGURE C-2: MONTHLY OPERATING GRADIENT PLOT**

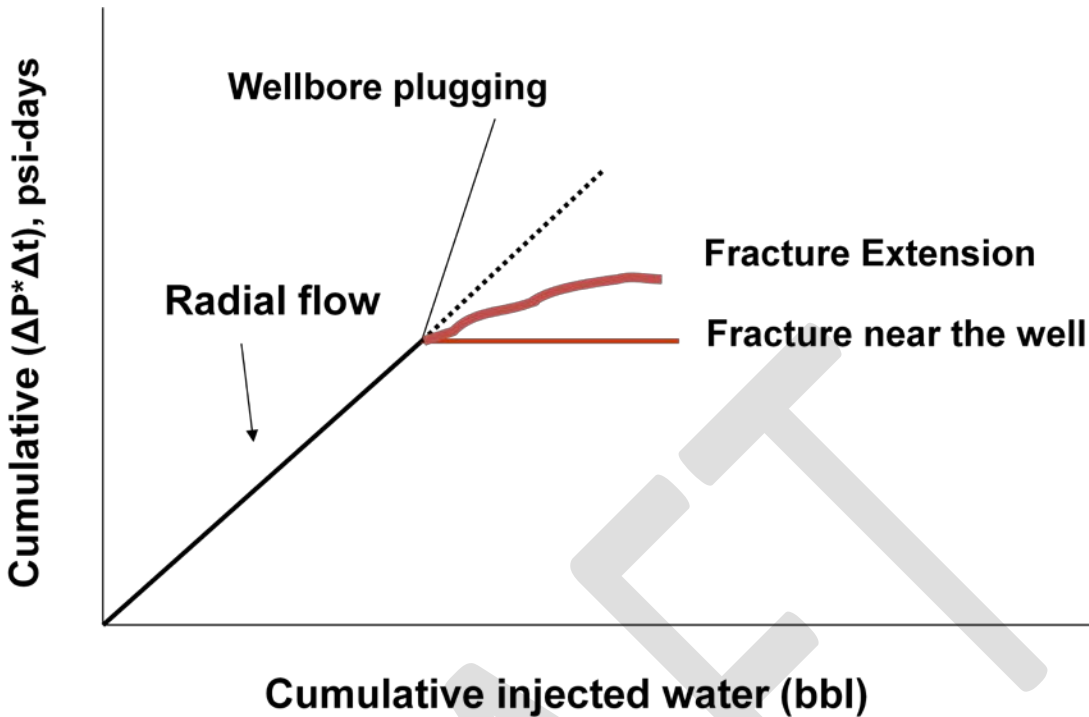


2

3 • **Hall Integral Plot (Figure C-3)**

- 4 ○ Developed to assess the effectiveness of water injection well stimulations (Hall,  
5 1963; Jarrell, et.al, 1991)
- 6 ○ Uses readily available operations data coupled with an estimate or measurement of  
7 static reservoir pressure around the injection well
- 8 ○ Based on integration of the steady state radial flow equation
- 9 ○ Widely accepted reservoir engineering methodology that is easily calculated in a  
10 spreadsheet for evaluating injection well performance and reservoir flow behavior
- 11 ○ Provides a long period observation of the injection zone
- 12     ▪ Useful for identifying changes in reservoir behavior over time
- 13 ○ Linear plot of a numerical integration of the steady state radial fluid flow equation in  
14 a form which yields straight line trends in operational data
- 15     ▪ Y-axis: Hall integral - Cumulative ( $\Delta P \cdot \Delta t$ ) function
- 16         •  $\Delta P$ : Injecting BHP-static BHP calculated for each measurement
- 17         •  $\Delta t$ : Time increment for measurements used in  $\Delta P$  calculation
- 18         • Cumulative sum of ( $\Delta P \cdot \Delta t$ ) as well operates
- 19             ○ Values will increase with cumulative operation time
- 20         • Hall integral is a function of the BHP difference between injection and  
21 shut-in conditions weighted by operating time increments
- 22             ○ Integral serves to “smooth out” noise commonly present in  
23 injection operating data
- 24     ▪ X-axis: Cumulative injection volume,  $W_i$

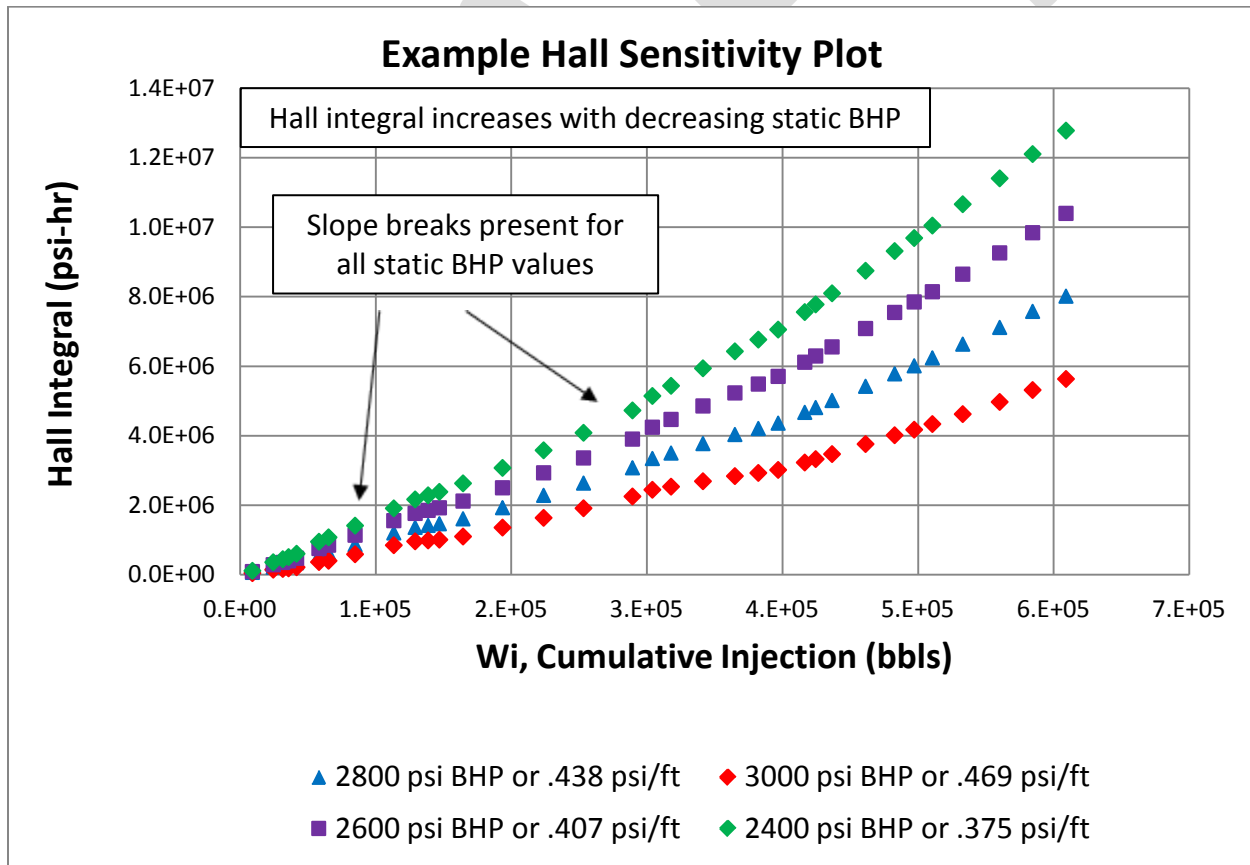
1 **FIGURE C-3: EXAMPLE HALL PLOT**



- Hall integral slope
  - Reflects the pressure response of the disposal well as fluid moves radially from the well
  - Changes indicate a well's completion condition or injection efficiency
  - Negative slope break (decline) associated with enhancement of injectivity
    - Fracturing of the well
  - Positive slope break (incline) indicates reduced injectivity
  - No slope break (straight line) represents radial flow
- Challenges:
  - Requires an assumption of the initial reservoir pressure if not provided
    - A measurement or good estimate of average static BHP is needed to develop a reliable calculation of the Hall integral
    - Conversion of surface pressure to BHP can be inaccurate because of friction pressure, especially for wells with high injection rates through smaller diameter tubing
    - Too high static reservoir pressure estimate can cause an incorrect calculation of the Hall integral
      - Hall integral should increase as long as injection is occurring
      - Wells used intermittently require data manipulation to keep the Hall integral positive

- May require sensitivity calculations for qualitative assessment of the Hall plot (Figure C-4)
  - Assume varying initial pressure values to see impact on shape of Hall integral response
    - Hall integral becomes larger with decreasing static pressure due to increased pressure difference between injection and shut-in pressures
  - Sensitivity calculations were performed using a range of assumed bottomhole static pressures for each case study well.
    - Overall slope change trends were not impacted, but the degree of slope change varied.

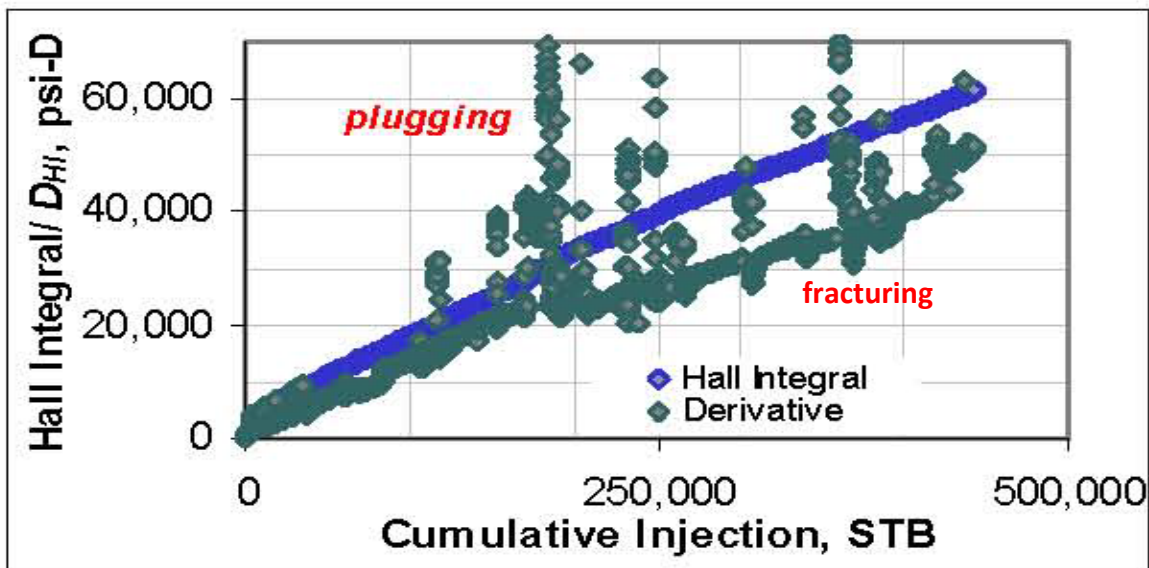
FIGURE C-4: HALL INTEGRAL SENSITIVITY PLOT



- Hall Derivative function plotted with Hall Integral (Figure C-5)

- SPE paper No. 109876 (Izgec and Kabir, 2009): Couples the Hall derivative and integral
  - Highlights well behavior patterns
    - Radial flow
    - Fracturing due to injection at or above formation parting pressure
    - Skin reduction due to acidizing
- Running slope of the Hall integral plot
  - Tends to be much noisier than the Hall integral
- Useful tool to identify if static pressure assumption for Hall integral was too high
  - Hall derivative should always be a positive value if Hall integral is increasing
- Linear plot of the Hall integral derivative versus date
  - X-axis: Cumulative injection,  $W_i$
  - Y-axis:  $(H_{i2}-H_{i1})/(W_{i2}-W_{i1})$ 
    - $(H_{i2}-H_{i1})$  represents difference between successive Hall integral values
    - $(W_{i2}-W_{i1})$  represents difference between successive cumulative injection values
- Location of derivative relative to the Hall integral indicates the completion condition of the well
  - Hall derivative located below Hall integral indicates fracturing
  - Hall derivative overlying Hall integral indicates radial flow
  - Hall derivative above the Hall integral indicates plugging occurring in the well

FIGURE C-5: HALL PLOT WITH DERIVATIVE (MODIFIED FROM FIG 1 FROM YOSHIOKA ET.AL. 2008, WITH PERMISSION)

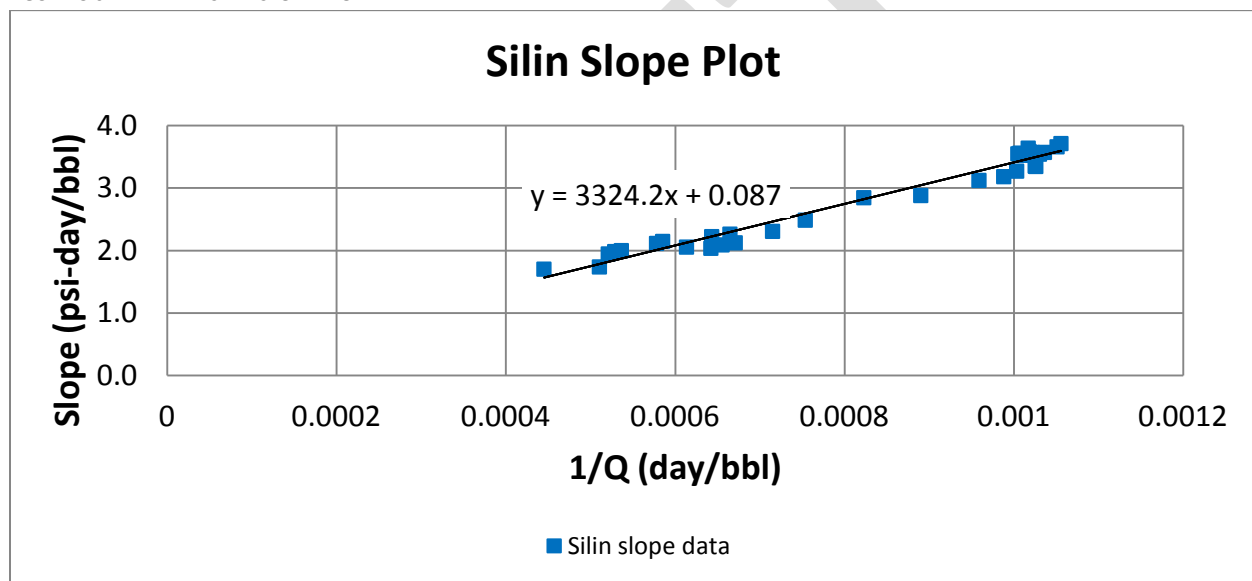


- Silin Slope Plot (Figure C-6)



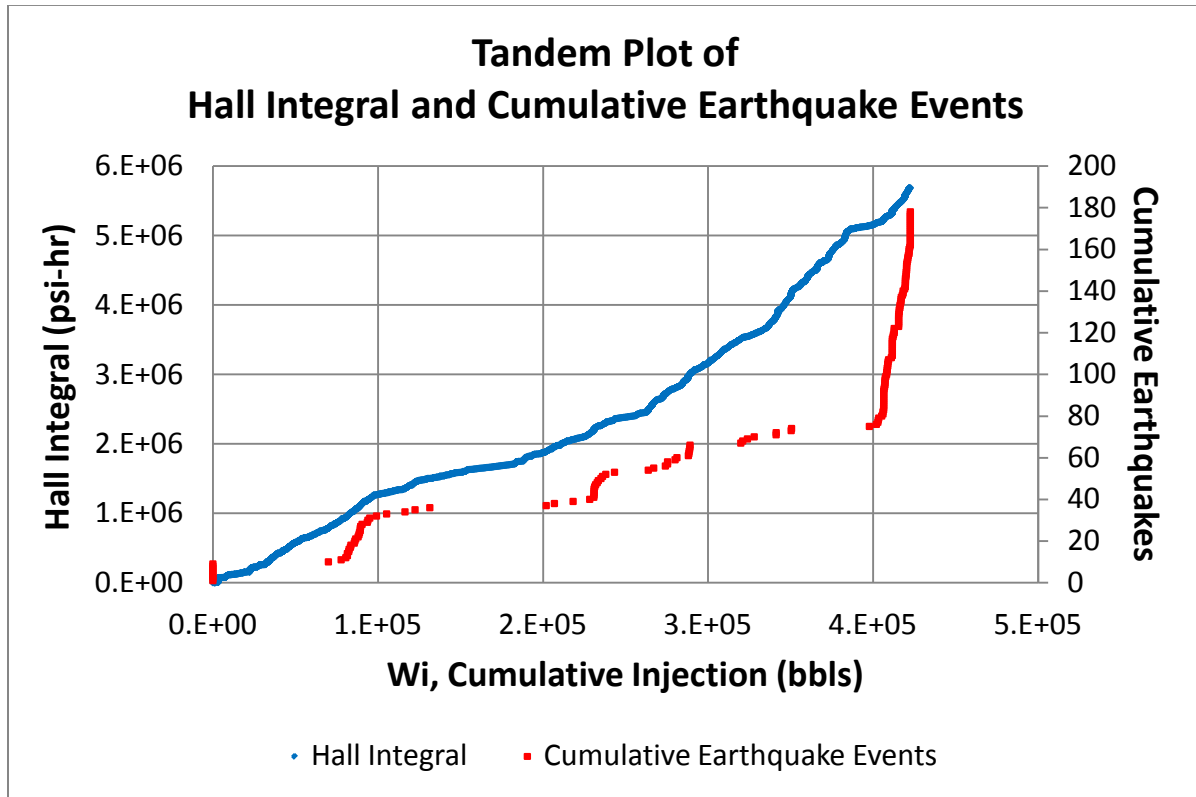
- Developed as a modification to Hall plot analysis to determine mean reservoir pressure around the injection well
- Linear plot of injection well operating data
  - Y-axis: Injection BHP divided by daily injection rate
  - X-axis: Reciprocal of the injection rate
- Data points are fitted to a best fit straight line
  - Slope of the resulting line yielding a mean reservoir pressure around the injector
- Challenges: Data scatter attributable to rate fluctuations in operational data
  - Leads to outliers in calculated values

FIGURE C-6: EXAMPLE SILIN SLOPE PLOT



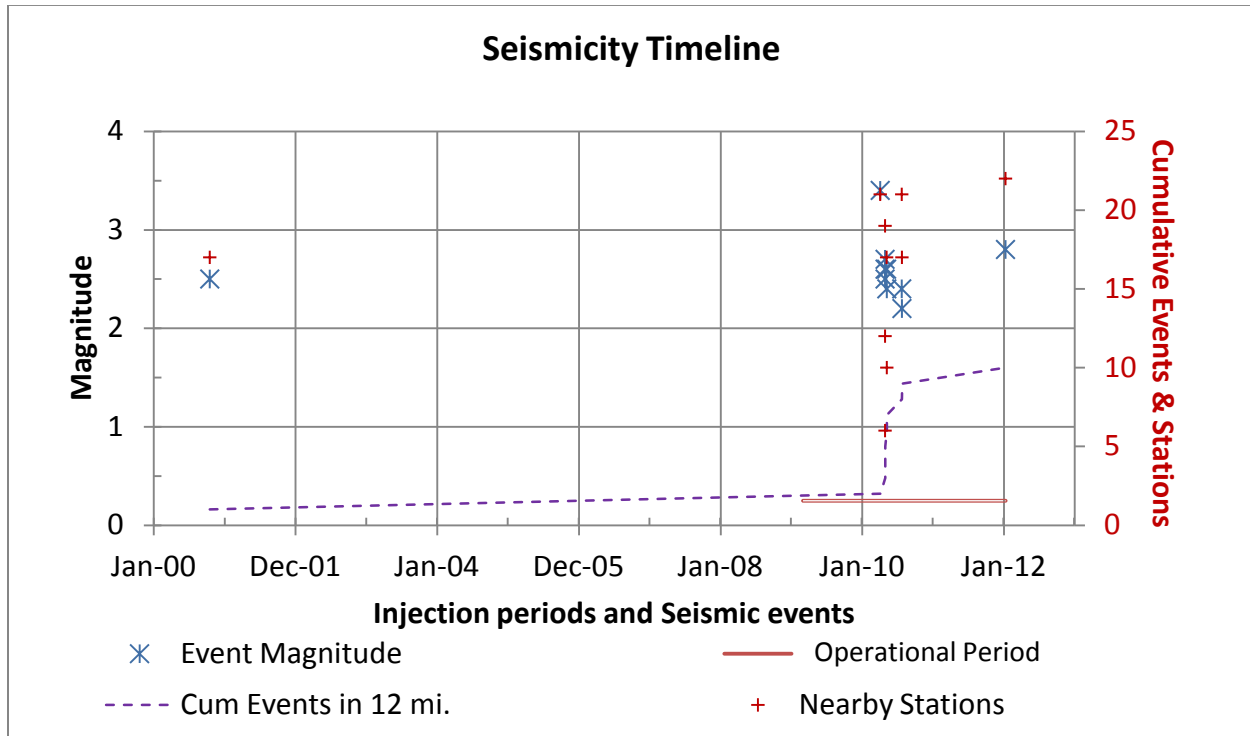
- Tandem Plot (Figures C-7)
  - Couples Hall integral response with cumulative earthquake events
    - Review for related trends
  - Plot Hall integral and cumulative earthquake events vs. cumulative injection

1 **FIGURE C-7: TANDEM PLOT – HALL INTEGRAL AND EARTHQUAKE CUMULATIVE FREQUENCY**



- 3 • Seismicity Timeline (Figure C-8)
- 4     ○ Plot of the earthquake magnitude and cumulative earthquake events versus the
- 5         operational period of the disposal well
- 6         ▪ X-axis: date
- 7         ▪ Y-axes: Earthquake magnitude and disposal well operational period
- 8             • *Secondary Y-axis: Earthquake cumulative events and number of*
- 9                 *recording stations*

1 **FIGURE C-8: SEISMICITY TIMELINE**

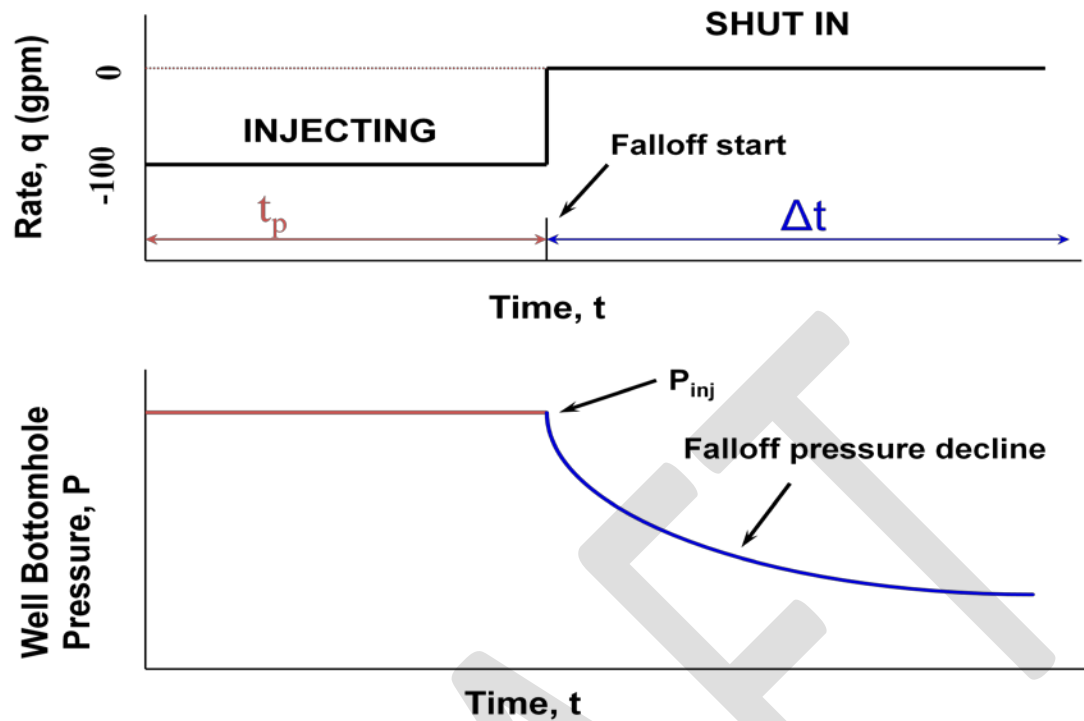


### 3 RESERVOIR ENGINEERING ANALYSIS OF PRESSURE TRANSIENT DATA

4 More refined well completion characteristics and reservoir descriptions are often obtained  
 5 through a designed test, such as a pressure transient test. Pressure transient tests typically run  
 6 in disposal wells include falloff tests, step rate tests, and injectivity tests. Pressure transient  
 7 tests are typically shorter in duration than the operational data periods, but reflect improved  
 8 data quality.

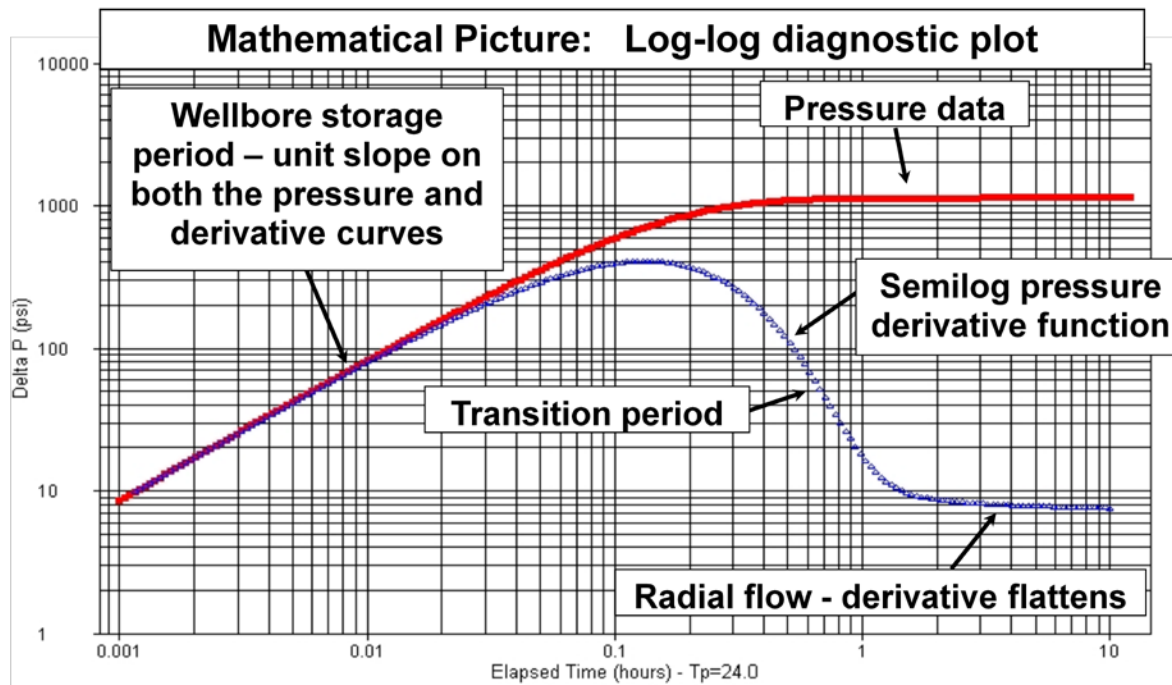
9 Analyses of pressure transient tests are performed using solutions to the unsteady state radial  
 10 diffusivity equation. One type of pressure transient test commonly associated with a disposal  
 11 well is a falloff test that measures the pressure decline by recording the well surface or  
 12 bottomhole pressure (BHP) when the well is shut-in. A falloff test sequence of events and  
 13 pressure response is shown in Figure C-9.

1 FIGURE C-9: FALLOFF TEST SEQUENCE OF EVENTS AND PRESSURE RESPONSE



2  
3  
4 Pressure transient tests are to a reservoir engineer as seismic surveys are to a geophysicist.  
5 Pressure transient tests provide short and intermediate distance mathematical “pictures” of the  
6 reservoir nature around the well when the data is analyzed against existing reservoir models  
7 and would be analogous to “a short term pinging of the reservoir with sonar” in the form of a  
8 pressure wave, whereas seismic surveys are acoustical “pinging” of the reservoir. Both use  
9 some type of energy wave to probe through the reservoir much like sonar “pings” the ocean or  
10 radar “pings” the airways. In both instances, the reservoir response to the associated “wave  
11 ping” is measured and analyzed. . A typical response (“ping”) of a falloff test when plotted in a  
12 mathematical picture form (log-log plot) is shown in Figure C-10, for a radially homogeneous  
13 reservoir.

1 **FIGURE C-10: LOG-LOG PLOT OF A FALLOFF TEST**



2

### 3 **PRESSURE TRANSIENT TEST PLOTS AND ANALYSIS APPROACH:**

4 Pressure transient theory correlates pressures and rates as a function of time and is the basis  
 5 for many types of well tests including both falloff and step rate tests. Pressure transient test  
 6 analyses revolve around solutions to a partial differential equation, called the radial flow  
 7 diffusivity equation. These solutions provide an injection well behavior model, a method for  
 8 reservoir parameter evaluation, and allow calculation of pressure and rate as a function of  
 9 distance.

10 The most common solution used applies to radial flow only. However, this solution is not  
 11 applicable in all geologic or well completion situations. By solving the diffusivity equation for  
 12 boundary conditions to address these geological or completion situations present at the  
 13 wellbore or in the reservoir, mathematical solutions specific to these situations are obtained.  
 14 Since these reservoir model solutions are based on a differential equation, their "signature" is  
 15 best presented in a log-log plot format.

16 The first step to analyzing pressure transient test is plotting the data in a format that allows for  
 17 comparison against the known reservoir model solutions. To compare actual test data to these  
 18 solutions requires plotting the actual data on a log-log plot to see if the data matches any of the  
 19 mathematical "picture" solutions. Therefore the log-log plot becomes a useful diagnostic tool  
 20 to analyze reservoir flow pathway characteristics and the injection well completion condition.

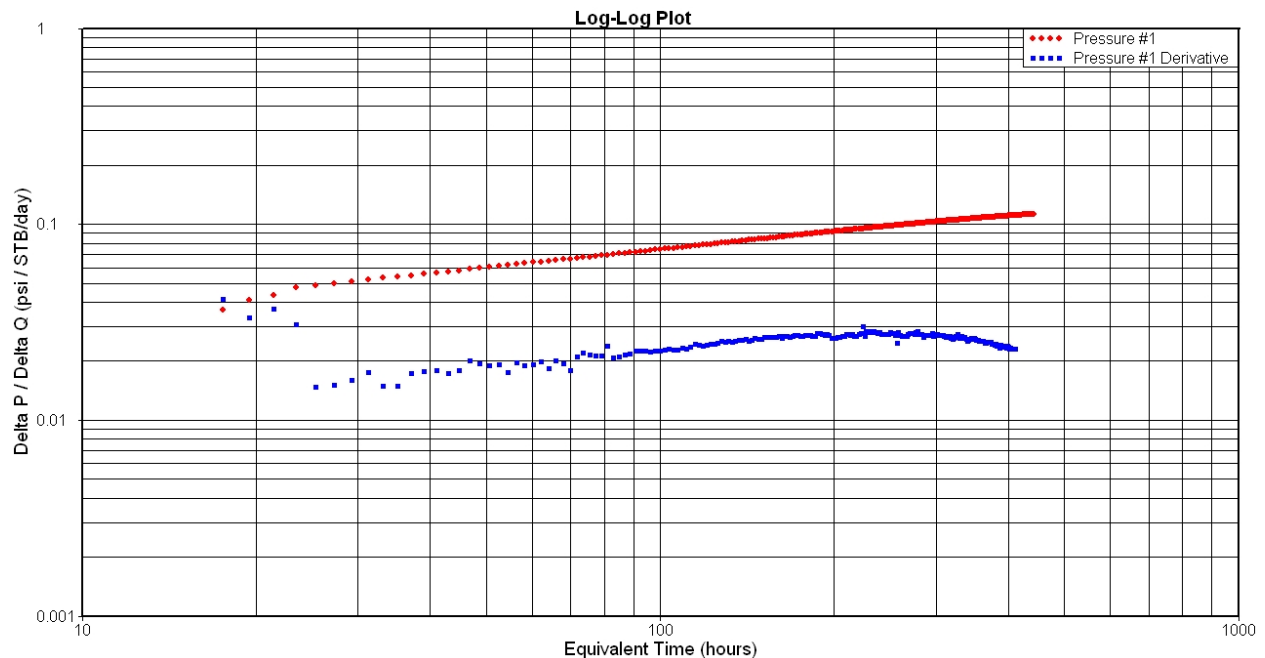
The log-log plot provides a window to see patterns of behavior at the well and into the reservoir. These patterns indicate the presence of different flow regimes. By identifying the flow regimes through a “mathematical picture” on the log-log plot, reservoir model solutions can then be matched to the test response to characterize the reservoir. An outline of a general approach to pressure transient test analysis and creating the various analytical plots is provided below.

#### Log-log diagnostic plot (Figure C-10 and C-11)

- General purpose diagnostic plot for pressure transient test analysis
  - Creates a mathematical “picture” of test data
  - Log-log plot “signature” reviewed for:
    - Slope patterns
      - Patterns represent flow regimes
      - Determines what portion of the test should be used in the reservoir analysis
      - Quantify reservoir characteristics from the responses
    - General log-log plot formatting typically consists of two curves
      - Pressure change ( $\Delta P$ ):
        - Y-axis: Pressure change ( $\Delta P$ ) between pressure prior to shut-in and measured pressure point at time  $\Delta t$  since last rate change occurred
        - X-axis: Delta time ( $\Delta t$ ), elapsed time since last rate change occurred
      - Semilog derivative ( $P'$ ):
        - Y-axis: Derivative or running slope of semilog plot of pressure vs.  $\Delta t$ , time since last rate change
        - X-axis: Delta time ( $\Delta t$ ), elapsed time since last rate change occurred
          - Time function is modified if injection rates are variable prior to the test period
    - Utility of pressure and semilog derivative curves
      - Pressure change curve
        - Limited use by itself
      - Derivative curve
        - Provides a “magnified” look at reservoir transient responses
        - Derivative offers more shape than the pressure curve
      - Enhances identification of various flow regimes representative of reservoir characteristics when derivative is coupled with pressure change curve
        - Spacing between the two curves impacted by completion condition

- Other uses of log-log plot
  - Derivative of specialty plots associated with specific flow regimes
    - Derivative is a running slope and magnifies slope changes
    - Can be calculated from a variety of plots
      - Flat derivative represents no slope change or a straight line on plot from which the running slope is being calculated

FIGURE C-11: LOG-LOG PLOT



- Flow regimes
  - Individual flow regimes present in the reservoir are identified by:
    - Characterized by mathematical relationships between injection rate, pressure and time
    - Descriptive shape of pressure and derivative curves
    - Sequential order starting at the well and moving farther into the reservoir as time elapses
    - Specific spacing between the curves
    - Provide a “picture” of what is going on in the reservoir
  - Typical flow regime patterns
    - Radial flow (Figure C-10)
      - Represents pressure movement radially away from the disposal well
      - Typical test response
        - Semilog plot: Straight line

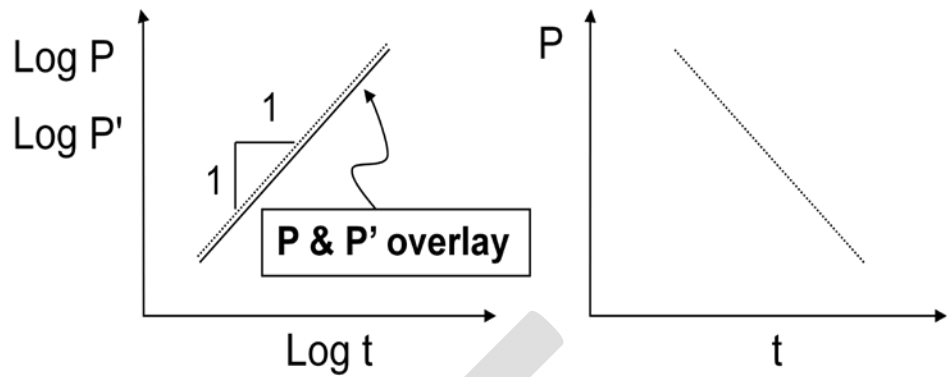
- Log-log plot: Simultaneous flat trends on pressure derivative and pressure change curves
- Other flow regimes
  - Linear flow: (Figure C-11)
    - Observed in hydraulically fractured well, channel sand, or some type geologic feature or reservoir boundary causing linear pressure flow to occur in the reservoir
    - Directionally oriented pressure response
    - Half slope trend on both the pressure change and pressure derivative curves
    - Specialty plot
      - Straight line on Pressure vs.  $\sqrt{t}$  time plot
      - Plot as a secondary derivative on log-log plot with flat trend (zero change in slope) during linear flow
  - Bilinear flow:
    - Observed in early time of low conductivity hydraulically fractured well
      - Applies to propped fractures
    - Often hidden by wellbore storage period
    - Quarter slope trend on both the pressure change and pressure derivative curves
    - Specialty plot
      - Straight line on pressure vs.  $t^{1/4}$  time plot
      - Plot as a secondary derivative on log-log plot with flat trend (zero change in slope) during bilinear flow
  - Spherical flow plot:
    - Partial penetration of injection zone open
    - Negative half slope trend on pressure derivative curve
    - Specialty plot
      - Straight line on pressure vs.  $1/\sqrt{t}$  time plot
      - Plot as a secondary derivative on log-log plot with flat trend (zero change in slope) during spherical flow
- Identifies well completion condition
  - Wellbore skin factor is reflected in the derivative
    - Dimensionless parameter describing the well completion condition
      - Negative skin: Enhanced completion
      - Positive skin: Damaged completion
      - Fractured wells exhibit very negative skin factors (-5 to -6)



- Other signatures
  - May identify reservoir boundaries such as pinchouts or faults if located in close proximity to the test well
    - Dependent on the duration of the test periods
  - Identify pressure interference
    - From other injection or producing wells in the same disposal zone
    - Reservoir influences, e.g. strong water drive
    - Formations with different rock properties and/or pressure in communication with the injection zone
- Type curves
  - Mathematical “pictures” or graphs of known reservoir response models
  - Analysis performed by “matching” test response against model “picture” (type curve)
    - Overlay type curve on test response since both are in log-log format
      - Match points provide quantitative reservoir parameters
      - Match two curves,  $\Delta P$  and  $P'$ , offering a better type curve match
        - Considers shape and separation between the curves
    - Typical slope patterns:
      - Wellbore storage (Figure C-12)
        - Unit slope trend on both pressure change and pressure derivative curves
      - Linear flow (Figure C-13)
        - Half slope trend on both the pressure change and pressure derivative curves
        - Derivative curve typically 1/3 log cycle below pressure curve
      - Derivative of linear ( $\sqrt{t}$ ) plot is a flat line representing a zero change in slope
      - Radial flow (Figure C-14)
        - Flat pressure change and pressure derivative curves
  - Challenges:
    - Planning of test to obtain good quality data
    - Derivatives magnify small changes in pressure trends so good recording devices are beneficial to reduce data scatter
    - Test not long enough to get out of wellbore storage

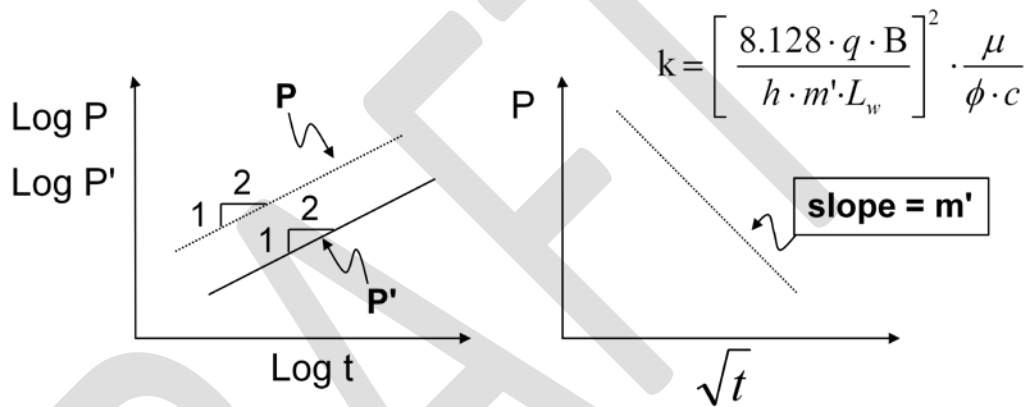
1 **FIGURE C-12: WELLBORE STORAGE SLOPE PATTERNS**

## Wellbore Storage



2  
3 **FIGURE C-13: LINEAR FLOW SLOPE PATTERN**

## Linear Flow

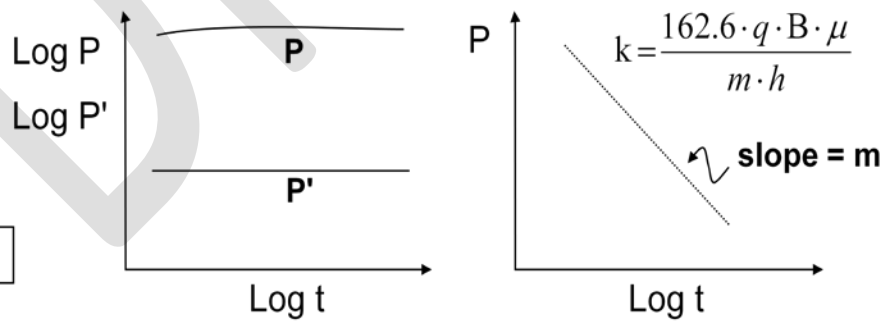


$$P' = dP/d(\log t)$$

Where  $L_w$  is the fracture length

6 **FIGURE C-14: RADIAL FLOW SLOPE PATTERNS**

## Radial Flow



$$P' = dP/d(\log t)$$

## *SPECIFIC ASPECTS OF PRESSURE TRANSIENT TESTS COMMONLY ASSOCIATED WITH DISPOSAL WELLS*

For purposes of this report, the focus was on pressure transient testing applications specific to disposal wells. The most applicable pressure transient tests to disposal wells are falloff, step rate and injectivity tests. Details relating to each type of test are provided below:

### FALLOFF TEST

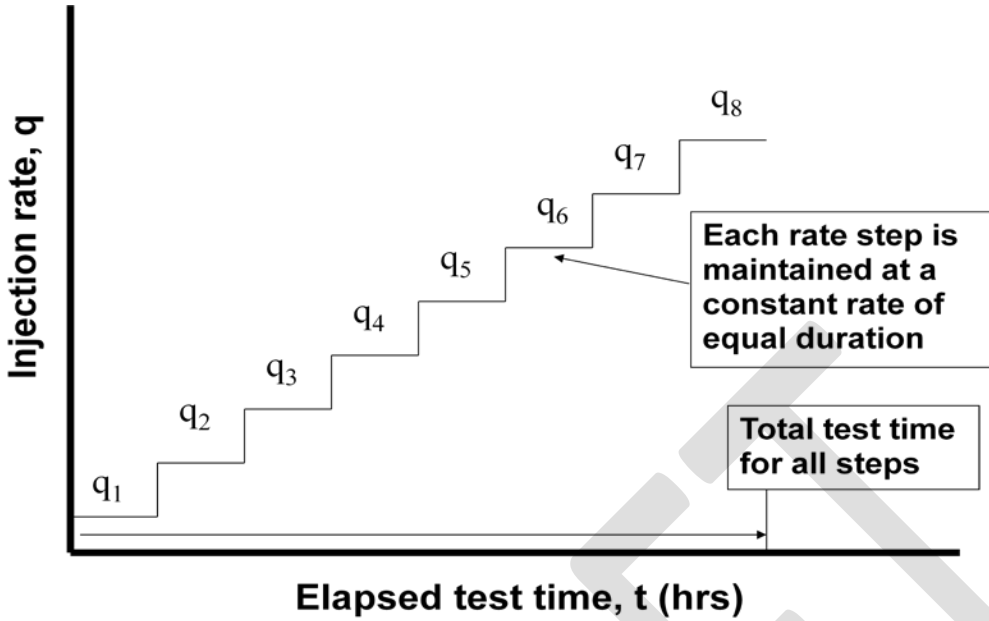
- Provides a measurement of the static formation pressure and the transmissibility of the injection zone or reservoir pathway
  - Transmissibility is a measurement of the formation's ability to transmit pressure and directly relates to the amount and lateral extent of pore pressure buildup in a formation
- Provides reservoir characteristics which can then be applied to predicting the amount and lateral extent of pressure buildup resulting from disposal operations.
- Involves shutting in the well and measuring the change in pressure versus elapsed time
  - Shutting in the well constitutes a rate change which triggers a pressure change in the form of a pressure decline over a period of time
- Evaluated using a log-log plot
  - Logarithmic y-axis:
    - Pressure change
      - Running cumulative value
      - Calculated by subtracting the pressure at the end of injection from each pressure value during the falloff period
    - Pressure derivative
      - Calculated from a running slope of a semilog plot of falloff pressure versus elapsed test time
  - Logarithmic x-axis: Elapsed test time
  - Time function on both the log-log and semilog plot is modified if the injection rate varied significantly prior to the falloff
  - The actual distance into reservoir observed during the test depends on the length of the test, completion condition of the well, and the characteristics of the reservoir
    - Lower permeable reservoirs may observe greater pressure changes over time, but the formation characteristics observed represent an area closer to the disposal well

### STEP RATE TESTS

- Estimates the formation parting pressure or fracture extension pressure

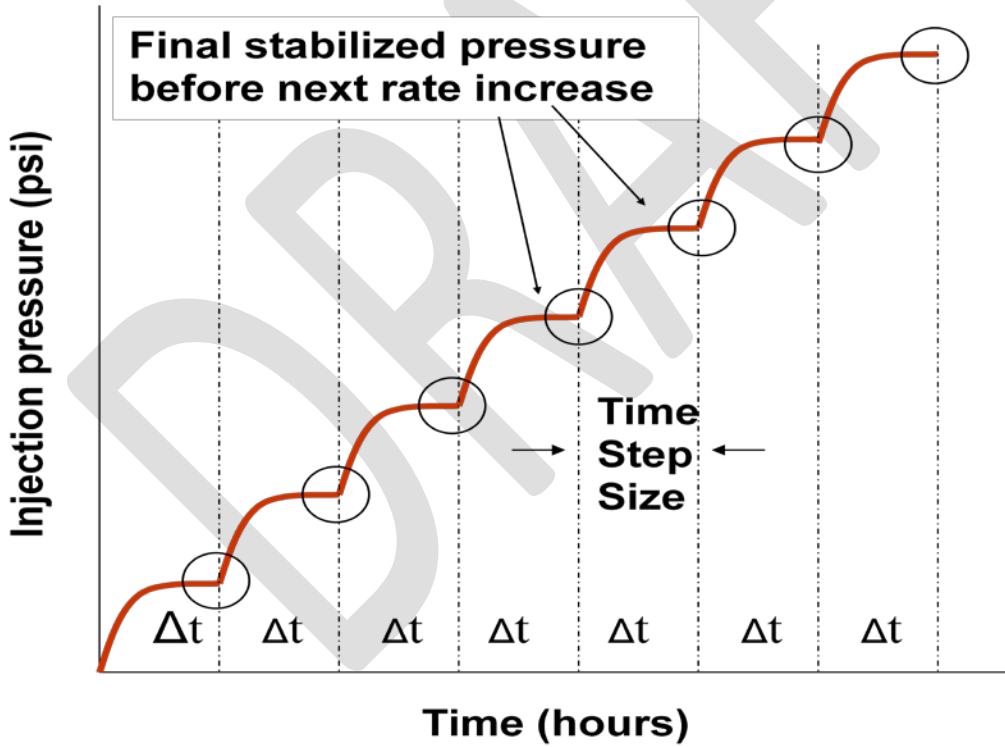
- Useful to prevent injection from fracturing the formation or extending existing fractures
- Test consists of a series of increasing injection rates as a series of rate steps (Figure C-15)
  - A constant rate is held for each rate step
  - Each rate step lasts for equal durations of time
  - Injection pressure should be stabilized at the end of each rate step (Figure C-16)
- Linear plot of injection pressure versus injection used for typical analysis (Figure C-17)
  - y-axis: Final injection pressure of each rate step
  - x-axis: Constant injection rate of each rate step
- Review plotted data for slope changes
  - Straight line(s) drawn through data
    - No break in a straight line through the points on the linear plot indicates fracture pressure not being observed during the test
    - Negative or declining slope break is observed
      - Draw straight line through points on both sides of the break
      - Intersection of lines drawn through groups of data points with different slopes provides an estimate of the fracture pressure
- Review continuous data for each rate step as individual injectivity tests
- Challenges:
  - Surface pressure measurements may provide misleading results
    - Friction pressure must be accounted for properly if using surface data involving high injection rates through smaller diameter tubing
    - Friction effects can mask the slope break
  - No break may be observed if disposal well is fractured prior to the first rate step
    - Initial rate too high
  - Not enough rate steps are included in the test to establish straight lines on the linear plot
  - Stabilized pressures are not reached during each rate step
  - Constant injection rates are not maintained during each rate step
    - Pump trucks often used to generate differing rates for each step
  - Rate and pressure measurement tend to be noisy if data recorded continuously

1 FIGURE C-15: STEP RATE TEST RATE SEQUENCE



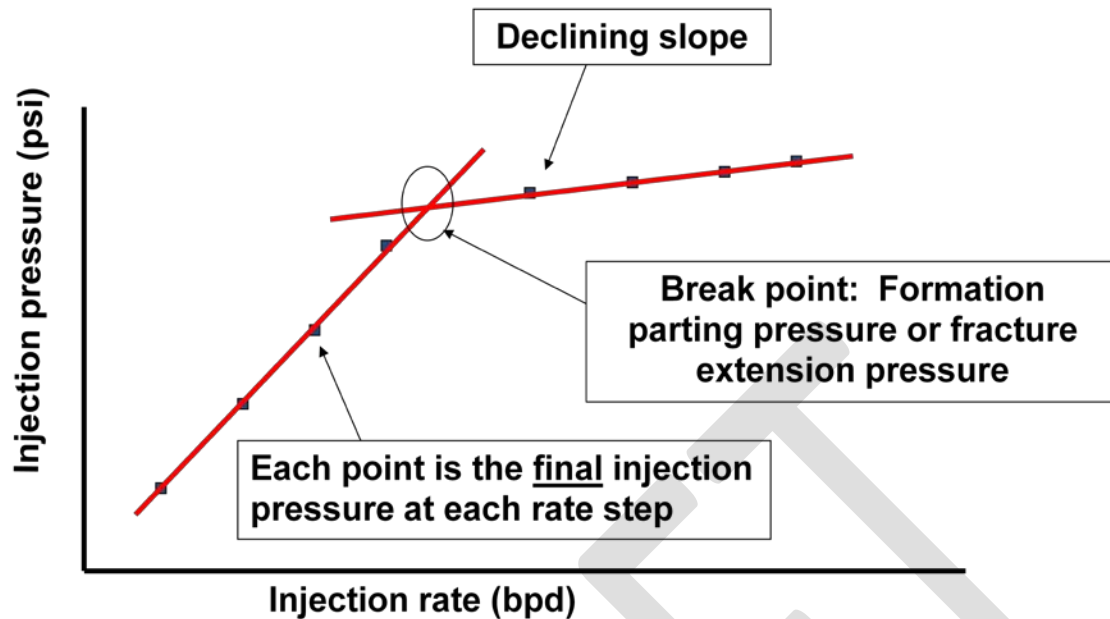
2

3 FIGURE C-16: STEP RATE TEST PRESSURE SEQUENCE



4

1 FIGURE C-17: STEP RATE TEST LINEAR PLOT

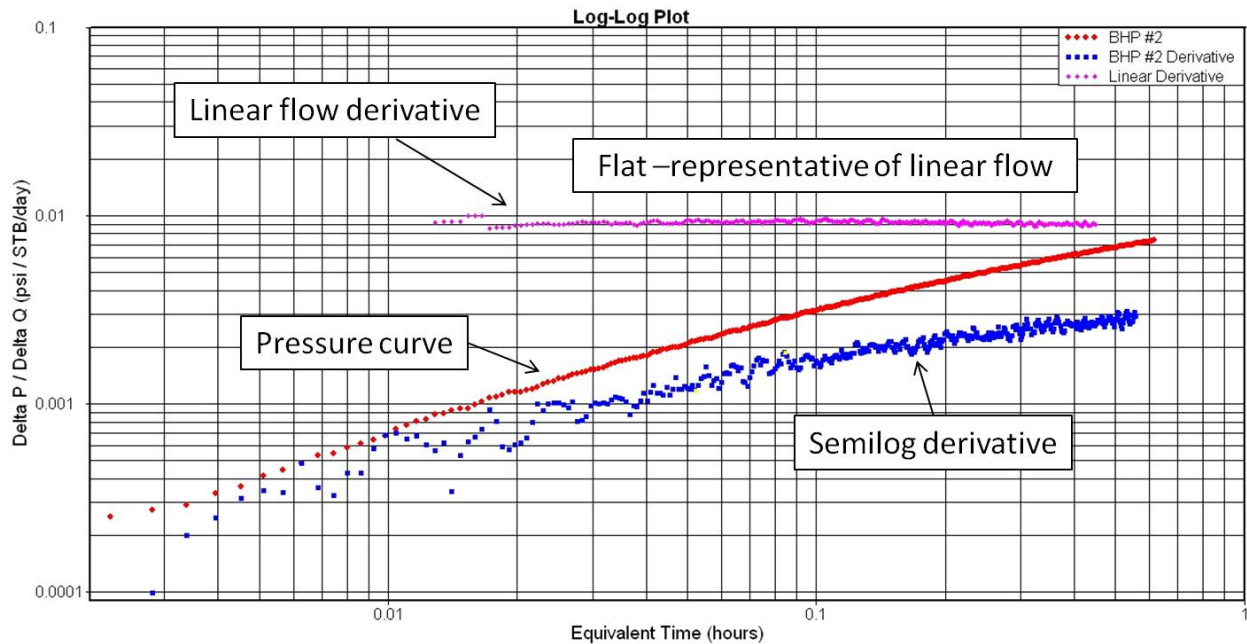


2

### 3 STEP RATE INJECTIVITY TEST PLOT

- 4 • Involves increasing the injection rate at the well and measuring the resulting change in
- 5 pressure increase
- 6 • Uses similar analysis methods as a falloff test
- 7 • Log-log diagnostic plot used to analyze each rate step (Figure C-18)
- 8     ○ Analyzes each rate step as an individual injectivity test
- 9     ○ Can provide information on near well reservoir characteristics that are not obtained
- 10 from the linear plot
- 11 • Limited duration of each rate step results in a shallower look into the reservoir
- 12 • Requires continuously recorded step rate pressure data to analyze
- 13 • Plot of each rate step is evaluated for a fracture or linear flow signature on the pressure and
- 14 derivative curve, and if present, the extent or fracture half length of the fracture
- 15 • Results compared with linear plot for confirmation of reservoir fracture pressure
- 16     ○ Test may show a radial flow characteristic in the early rate steps and a fracture
- 17 signature in the late rate steps if the formation parting pressure is exceeded
- 18 • Challenges:
- 19     ○ Data can be “noisier” since injection is occurring and passing by the pressure gauge
- 20     ○ Friction pressure should be accounted for if surface pressures are used in the
- 21 analyses

1 **FIGURE C-18: INDIVIDUAL RATE STEP LOG-LOG INJECTIVITY PLOT**



#### 2 *HOW CAN THE OPERATIONAL DATA AND PRESSURE TRANSIENT TEST ANALYSES BE USED?*

3  
4  
5 Pressure change in the reservoir can induce seismicity in certain geologic settings. The  
6 reservoir engineering approaches may be useful for linking the pressure behavior of the  
7 injection well to seismicity and area geology for assessing if a reservoir is appropriate for a  
8 disposal zone. Pressure transient testing identifies flow behavior which indicates how the  
9 reservoir pathway pressure increases are distributed away from the disposal well and, in the  
10 case of a falloff, measures static pressure for assessing reservoir pressure buildup. For  
11 example, pressure increases from a disposal well exhibiting a fracture or linear flow  
12 characteristic may extend directionally over greater distances from the well than would be  
13 expected for radial flow, similar to a garden hose nozzle versus a sprinkler.

14 One question that repeatedly surfaced during this effort, including in the literature, related to  
15 existing mechanisms of transferring pore pressure buildup over substantial distances in  
16 reservoirs. EPA Region 6 designed and performed the evaluation of a Class II disposal well  
17 suspected of impacting abandoned wells approximately one mile away from the disposal well.  
18 No seismic activity occurred as a result of injection operations with this particular well, but the  
19 case illustrates preferential pressure distribution over great distances in a formation suspected  
20 of containing a geologic anomaly. (Appendix I provides the details of the case history.)

21 As discussed in Appendix I, EPA directed the pressure transient testing of wells to determine  
22 whether reservoir pressure buildup could be attributed to the disposal well operations. A

falloff test was conducted in the suspect disposal well. An interference test was also designed using the disposal well as the source well and the impacted wells as observation wells. The log-log diagnostic plot of the falloff test conducted in the disposal well indicated the well was connected to a fracture or fault system even though this type of geologic environment was not readily evident from available geologic data. The location of impacted area wells supported a preferential directional flow pattern seen in the falloff test. The pressure responses in one of the two observation wells located a mile away decreased by over 200 psi within a few hours of shutting the disposal well during the stabilization test period and increased by approximately 150 psi after initiating injection in the disposal well. Data from wells monitored outside the preferential flow direction showed no pressure response. The pressure responses provided conclusive evidence of the communication between the disposal well and impacted abandoned wells. Based on this testing, the state UIC regulators closed the disposal well.

For disposal wells identified as injecting into linear or fractured flow regimes, expanding the area reviewed for site characterization may be useful to describe potential reservoir behavior. Typical pressure buildup calculations are based on the assumption that injection occurs into a radially, homogeneous, infinite acting reservoir. In a homogeneous reservoir, the pressure dissipates equally in all directions away from the wellbore. Naturally fractured reservoirs generally do not meet these assumptions. Therefore, pressure buildup distribution from a disposal well injecting into a fractured formation may require a more complex evaluation than for wells injecting into a formation exhibiting radial flow characteristics.

Analysis of the operating data coupled with any available pressure transient tests such as falloff and step rate tests for a disposal well can provide critical details, both geologically and hydraulically, about the nature and conditions on the injection reservoir. An attempt should be made to correlate anomalous test results to seismic events to determine if additional data gathering, monitoring, or testing is warranted. Since operating data are readily available and require no additional monitoring, the reservoir engineering approach for analysis of such data provides an established technical methodology that may correlate existing well data to seismic events in the area.

#### *HOW DID THE WG PERFORM THE CASE STUDY EVALUATIONS?*

- Software requirements
  - Microsoft Excel® was used for the evaluation of operation data
    - Required assumptions to generate some parameters or functions used
  - PanSystem® software was used to analyze pressure transient data
- Tasks performed for all case study areas
  - Obtained injection pressure, rate, and time data for wells within the areas



- Operational analysis plots generated:
  - Overview plot
  - Operating gradient plot
  - Hall integral plot with derivative
  - Silin slope plot
  - Tandem plot
    - Relates cumulative earthquakes to Hall integral
- Pressure transient test (falloff and step rate) analysis plots generated when data available:
  - Cartesian overview plot
  - Log-log plot
  - Type curve match where applicable
  - Step rate test linear plot
- The detailed assessment for each case study is included in the respective case study appendices

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## APPENDIX D: NORTH TEXAS CASE STUDY AREAS: DFW AND CLEBURNE

|   |      |
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| Geologic Setting .....  | D-1  |
| Oil and Gas Activity .....  | D-2  |
| History of Seismicity.....  | D-2  |
| Reservoir Engineering Data Collected .....                                    | D-2  |
| Data Reviewed and Processed for Reservoir Engineering Analysis.....           | D-2  |
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### *BACKGROUND*

Several small (Magnitude 1.7 to 3.3) earthquakes occurred in the central part of the Dallas - Fort Worth metroplex near DFW international airport starting on October 31, 2008. The two case study wells in this area began operations in June 2007 and March 2008. Seismic activity (Magnitude 2.0 to 3.3) near the town of Cleburne started on June 2, 2009. The seven case study wells in this area began operations between October 2003 and August 2007. Both areas are located in north central Texas and the eastern portion of the Barnett shale play (Figure D-1).

### *GEOLOGIC SETTING*

The DFW and Cleburne case studies are located within the Fort Worth Basin. The generalized east-west cross-section (Figure D-2) shows the relationship of the formations bounded on the east by the Ouachita thrust fault against basement rocks. The generalized north-south cross-section in Figure D-3 shows Pennsylvanian age faulting (Bruner and Smosna, 2011). A third faulting style appears in the basin, resulting from collapsed chimney structures above Ellenburger karst sink holes and caverns illustrated in Figure D-4 (Bruner and Smosna, 2011; McDonnell, 2007; Montgomery et al., 2005; Steward, 2011). The case study Class II disposal wells are completed in the Ellenburger formation.

1 The Barnett Shale lies below the Mississippian-Pennsylvanian unconformity, and lies  
2 unconformably over Ordovician carbonates (Viola, Simpson and Ellenburger formations). As  
3 shown in Figures D-2 and D-3, the Barnett shale can lie directly on the Ellenburger.

4 During a meeting between EPA Region 6 and an area operator, Chesapeake Energy  
5 (Chesapeake), Chesapeake presented geologic data gathered in portions of the Fort Worth  
6 Basin which indicated there are no obvious Ellenburger karst features in the DFW airport area;  
7 however, the area around Cleburne showed significant karst features. The presentation  
8 displayed a major normal fault with approximately 600 feet of displacement, down to the east-  
9 southeast, in the DFW area. This fault is located about a mile west of the Ellenburger disposal  
10 well, DFW C1DE.

#### 11 *OIL AND GAS ACTIVITY*

12 The Barnett Shale production discovery took place in 1981 in Newark East field, in Wise County.  
13 Since 2002, most Barnett shale wells are horizontally drilled with 1000 to 3500 foot lateral legs  
14 (Martineau, 2007). In Newark East, the top Barnett Shale depth ranges from 6900 to 7500 feet,  
15 with a thickness varying from 200 to over 700 feet near the Muenster Arch in the northeast  
16 (Montgomery et al., 2005).

#### 17 *HISTORY OF SEISMICITY*

18 Prior to October 2008, no earthquakes were reported in any of the six seismicity databases,  
19 (ANSS, SRA, NCEER, USHIS, CERL and PDE), within 40 miles of the Dallas Fort Worth international  
20 airport or the Cleburne area.

#### 21 *RESERVOIR ENGINEERING DATA COLLECTED*

22 The RRC website provides public access to downloadable permitting-related documentation  
23 and annual operating reports. Permitting documents provided details concerning completion  
24 depths, construction information, and permit conditions for the case study wells. Annual  
25 operation reports provided monthly injection volumes and average and maximum wellhead  
26 pressures.

#### 27 *DATA REVIEWED AND PROCESSED FOR RESERVOIR ENGINEERING ANALYSIS*

28 Surface pressures were converted to approximate bottomhole pressure (BHP) at tubing seat  
29 depths. For this conversion, a brine specific gravity of 1.05 (roughly equivalent to 45,000 ppm  
30 chlorides) was assumed. Tubing dimensions, length and inside diameter, were taken or  
31 estimated from permit documentation. To determine friction pressure, the Hazen-Williams  
32 friction loss correlation with a friction factor, C, of 100 for steel tubing was used. BHPs were  
33 calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the

1 calculated friction pressure loss. After operating BHPs were estimated from the reported  
2 tubing pressures, seven operating data-related plots were prepared for selected wells within  
3 the case study areas. The seven plots were a seismicity timeline; an operational overview data  
4 plot; operating pressure gradient plot; a Hall integral and derivative plot based on the average  
5 tubing pressure; Silin slope plot; and a tandem plot. The tandem plot combines the Hall  
6 integral with cumulative area earthquake events against a common scale of cumulative disposal  
7 volume.

## 8 *OPERATIONAL ANALYSIS OBJECTIVES*

9 Operational analysis plots were prepared to assess well operating data. Details about the  
10 following plots were previously discussed in Appendix B:

- 11 • Seismicity timeline
- 12 • Operational data overview plot
  - 13 ○ Identify trends in the basic operating data such as increased surface pressure or
  - 14 injection volumes over the well's life
- 15 • Operating gradient plot
  - 16 ○ Indicator of whether a well's operating pressure approached a rule of thumb
  - 17 fracture gradient value of 0.7 psi/foot
  - 18 ○ Calculated by dividing the computed operating BHP by the depth of the most recent
  - 19 tubing seat value
  - 20 ○ Generally, tubing seats were within 100 feet of the top of the completion interval in
  - 21 each well
- 22 • Hall integral plot
  - 23 ○ Assess injectivity enhancements
  - 24 ○ Requires estimate of average reservoir pressure
  - 25 ○ Sensitive to the average pressure value used
- 26 • Silin slope plot
  - 27 ○ Estimate average pressure around the injection well
  - 28 ○ Silin result compared to assumed value in Hall integral calculation
- 29 • Tandem plot
  - 30 ○ Correlate earthquake events to operational data
    - 31 ■ Plot Hall Integral and cumulative earthquake events
      - 32 • Cumulative earthquake events multiplied by factor to scale the event
      - 33 trend to magnitude of cumulative water injection volumes
    - 34 ■ Plot operational rate history and earthquake events

## DFW AIRPORT CASE STUDY AREA

The DFW airport area earthquake swarm, within a five mile radius of the case study wells discussed below, is shown in map view on Figure D-5, and in seismicity timeline form of events on Figure D-6. No earthquake events were located within 5 miles of DFW North A1DM. Figure D-7 shows the earthquake events within a 5 mile radius of DFW C1DE. The figures are based on information from the ANSS and NEIC catalogs, plus the SMU portable arrays that were described by Frohlich et al. (2011). While Eisner discusses seismic information recorded by Chesapeake (Eisner, 2011; Appendix H), details were not provided so this information was not incorporated in this report.

TABLE D-1: DFW AIRPORT AREA SEISMICITY THROUGH 1/31/2012

| Year | Starting Event | Number of Events | Magnitude |      |      | Ending Event |
|------|----------------|------------------|-----------|------|------|--------------|
|      |                |                  | Min.      | Avg. | Max. |              |
| 2008 | 10/31/2008     | 19               | 1.7       | 2.4  | 3.0  | 12/1/2008    |
| 2009 | 5/16/2009      | 4                | 2.6       | 2.9  | 3.3  | 5/16/2009    |
| 2010 |                | 0                |           |      |      | 12/31/2010   |
| 2011 | 8/7/2011       | 1                | 2.6       | 2.6  | 2.6  | 8/7/2011     |
| 2012 |                | 0                |           |      |      | 1/31/2012    |

The following two wells were investigated by the Railroad Commission of Texas (RRC), in response to the earthquakes starting in 2008. Both suspect wells were disposal wells completed in the Ellenburger formation. The wellbore diagram for the DFW C1DE is shown in Figure D-8. Permit information is summarized in Table D-2 and listed below:

### DFW AIRPORT VICINITY DISPOSAL WELLS

**DFW C1DE:** UIC Permit 97642; Maximum permit pressure of 5023 psig and injection rate of 25,000 BPD; Total depth 14,375'; Initial injection September 2008; Final injection August 2009; Authorized injection zone 10,047'-14,375' openhole; Injection formation - Ellenburger; Current well status - shut-in.

**DFW North A1DM:** UIC Permit 98402; Maximum permit pressure of 4400 psig (amended from 4575) and injection rate of 25,000 BPD; Total depth 13,165'; Initial injection November 2007; Authorized injection zone 8,802'-13,165'; Injection formation Ellenburger.

TABLE D-2: DFW AIRPORT AREA DISPOSAL WELL CONSTRUCTION

| Well           | Total Depth | Long String Casing Diameter and Seat | Tubing Diameter and Seat Depth | Perforations             |
|----------------|-------------|--------------------------------------|--------------------------------|--------------------------|
| DFW C1DE       | 14,375'     | 7" to 10,047'                        | 4 ½" to 9997'                  | Openhole 10,047'-14,375' |
| DFW North A1DM | 13,165'     | 7" to 8800'                          | 4 ½" to 8800'                  | Openhole 8802' – 13,165' |

## OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS

Only operational data was available so no pressure transient test analyses were conducted in the two DFW airport area case study wells. Figures D-9 through D-12 provide an operational data overview and calculated operational pressure gradient plots for both wells. Figures D-13 and D-14 are Hall integral with derivative plots and Figures D-15 and D-16 are the Silin slope plots for each well. Table D-3 summarizes data associated with the Hall integral and Silin slope plot and compares the average pressure estimated for the Hall integral to the value determined from the corresponding Silin slope plot.

TABLE D-3: DFW AIRPORT AREA HALL AND SILIN SLOPE PLOT RESULTS

| Well           | Hall Assumed<br>Average Pressure<br>(psi) | Slope Plot Average<br>Pressure<br>(psi) |
|----------------|---|---|
| DFW C1DE       | 4600                                      | 6533                                    |
| DFW North A1DM | 3900                                      | 5206                                    |

### DFW C1DE

- Overview plot (Figure D-9)
  - Well shut-in during August 2009
- Operating pressure gradient plot (Figure D-11)
  - Remained below the 0.7 psi/ft rule-of-thumb fracture gradient
- Hall integral and derivative plot (Figure D-13)
  - Indicated normal injection
- Silin slope plot (Figure D-15)
  - Slope of the straight line trend estimated an average reservoir pressure of 6533 psi
  - Higher than the calculated injecting BHP values
  - Value higher than the 4600 psi value used for the Hall integral calculation
- Tandem plot (Figure D-17)
  - Showed no correlation between the Hall integral response and cumulative earthquake trend

### DFW North A1DM

- Overview plot (Figure D-10)
  - Well still currently active
  - Injection pressure constant while rate declining during 2010 and 2011
- Operating pressure gradient plot (Figure D-12)
  - Remained below the 0.7 psi/ft rule-of-thumb fracture gradient

- Hall integral and derivative plot (Figure D-14)
  - Low monthly volume suggests well did not operate continuously throughout the month, but hours operational were not reported to verify
  - Showed a negative slope break, but questionable due to data quality
    - Hall derivative remained below the Hall integral trend during period with negative slope break
- Silin slope plot (Figure D-16)
  - Slope of the straight line trend estimated an average reservoir pressure of 5206 psi
  - Higher than some the calculated injecting BHP values
  - Value higher than the 3900 psi value used for the Hall integral calculation
- Tandem plot (Figure D-18)
  - No earthquakes occurred within a 5 mile radius of the well

#### ACTIONS TAKEN BY UIC REGULATORY AGENCY IN DFW AIRPORT STUDY AREA

Following the seismic events, the RRC worked with the operator of the nearest disposal well, DFW C1DE. The operator voluntarily shut the well in, though they do not consider the evidence for induced seismicity to be conclusive. The second well, the DFW North A1DM remained operational. The RRC reviewed its permit actions for this well, as well as other wells in the area in an effort to determine if the activity could have been predicted. No indications of possible induced seismicity were found in these reviews. RRC also inspected the area to verify no measurable harm or potential hazard related to the events. In follow-up, the RRC consulted with industry representatives, and researchers at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M University, and continues to monitor developments and research related to induced seismicity.

#### CLEBURNE AREA CASE STUDY

The Cleburne area earthquake swarm, within a five mile radius of the seven case study wells discussed below, is shown in map view on Figure D-19, and in a timeline form on Figure D-20. Expanded views of earthquake events near the case study wells are shown in Figures D-21 through D-24. A summary of the Cleburne area earthquakes recorded in the ANSS and NEIC databases is included in Table D-4. Information from the SMU portable array is being interpreted and publication is anticipated in late 2012.

TABLE D-4: CLEBURNE AREA SEISMICITY THROUGH 1/31/2012

| Year | Starting Event | Number of Events | Magnitude |      |      | Ending Event |
|------|----------------|------------------|-----------|------|------|--------------|
|      |                |                  | Min.      | Avg. | Max. |              |
| 2009 | 6/2/2009       | 9                | 2.0       | 2.4  | 2.8  | 10/1/2009    |

|      |           |   |     |     |     |            |
|------|-----------|---|-----|-----|-----|------------|
| 2010 | 11/8/2010 | 2 | 2.1 | 2.3 | 2.5 | 11/12/2010 |
| 2011 |           | 0 |     |     |     |            |
| 2012 | 1/18/2012 | 1 | 3.3 | 3.3 | 3.3 | 1/18/2012  |

1

2 The following seven wells were investigated in relation to the earthquakes in 2010. All the  
3 wells are commercial disposal wells completed in the Ellenburger formation, except the  
4 Johnson County SDW 1. Permit information is summarized in Table D-5 and listed below:

5 **CLEBURNE VICINITY DISPOSAL WELLS**

6 *Sparks Drive SWD 1*: UIC Permit 93369; Maximum permit pressure 2900 psig; 9,000 BPD; TCEQ  
7 Class I permit WDW 401; ; Maximum permit pressure 5149 psig; ; 8,022 BPD Total Depth:  
8 9,134'; Initial Injection: December 2005; 7,509'-9,134' openhole; Ellenburger commercial  
9 disposal.

10 *S Mann SWD 1*: UIC Permit 94931; Maximum permit pressure 3708 psig; 20,000 BPD; Total  
11 Depth: 9,071'; Recompleted and initial Injection: October 2006; 7,627-9,071' openhole;  
12 Ellenburger commercial disposal.

13 *South Cleburne SWD 1*: UIC Permit 94930; Maximum permit pressure 3650 psig; 20,000 BPD;  
14 Total Depth: 10,952'; Initial Injection: October 2006; Final injection: July 2009; Authorized  
15 interval 7,300-10,800'; Ellenburger commercial disposal; temporarily abandoned.

16 *Johnson Salty SWD 2*: UIC Permit 96487; Maximum permit pressure 3500 psig; 30,000 BPD;  
17 Total Depth: 10,000'; Initial Injection: January 2007; 7,210-10,000'; Ellenburger commercial  
18 disposal.

19 *Johnson Salty SWD 3*: UIC Permit 96488; Maximum permit pressure 3500 psig; 30,000 BPD;  
20 Total Depth: 12,000'; Initial Injection: February 2008; 7,200-10,000'; Ellenburger commercial  
21 disposal.

22 *Cleburne Yard 1*: UIC Permit 97113; Maximum permit pressure 2300 psig; 15,000 BPD; Total  
23 Depth: 10,128'; Recompleted and initial Injection: August 2007; 7,650-11,500'; Ellenburger  
24 commercial disposal.

25 *Johnson County SDW 1*: UIC Permit 95581; Total Depth: 11,213'; Maximum permit pressure  
26 3800 psig; 25,000 BPD; Initial Injection: January 2007; 7,995-10,821'; Ellenburger, open hole.



1 **TABLE D-5: CLEBURNE AREA DISPOSAL WELL CONSTRUCTION**

| Well                         | Total Depth | Casing Diameter and Setting Depth | Tubing Diameter and Seat                         | Perforations                                      |
|------------------------------|-------------|-----------------------------------|--|---|
| Sparks Drive SWD 1 (WDW-401) | 9134'       | 5 ½" at 7509'                     | 3 ½" at 7421'                                    | Openhole 7509' to 9134' Fill at 7882' in Aug 2011 |
| S. Mann SWD 1                | 9071'       | 7" at 7627'                       | 3 ½" at 7425'                                    | Openhole 7627' to 9071'                           |
| South Cleburne SWD 1         | 10,952'     | 7" at 10,903'                     | 4½" at 10,349'                                   | 10,422'-10,755'                                   |
| Johnson Salty SWD II Well 2  | 9810'       | 7" at 9808'                       | 4" at 6950' Replaced w/ 4½" at 7080' in Mar 2011 | Disposal interval 7210' to 10,000'                |
| Johnson Salty SWD III Well 3 | 9799'       | 7" at 9799'                       | 4" at 7100' Replaced w/ 4½" at 7750' in Mar 2011 | Disposal interval 7850' to 10,000'                |
| Cleburne Yard 1              | 10,128'     | 7" at 7850'                       | 4 ½" at 7765'                                    | Injection interval 7,650-11,500'                  |
| Johnson County SWD 1         | 11,213'     | 7" at 7994'                       | 4 ½" at 7981'                                    | Openhole 7,995-10,821'                            |

2 **ADDITIONAL DATA COLLECTED**

3 The Sparks Drive SWD is dually permitted as a Class II commercial with the RRC and as the  
4 WDW-401 Class I disposal well with the Texas Commission on Environmental Quality (TCEQ).  
5 Class I wells are required to conduct annual falloff tests. In this appendix Sparks Drive SWD 1  
6 and WDW-401 will be referred to as the Sparks Drive SWD 1. EPA acquired the 2005, 2006, and  
7 2008 through 2011 annual falloff pressure transient tests for the Sparks Drive SWD 1. Analyses  
8 of these pressure transient tests for Sparks Drive SWD 1 are included in this case study. No  
9 pressure transient tests were available for the other wells. The wellbore schematic for the  
10 Sparks Drive SWD 1 is shown in Figure D-25.

11 **OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS**

12 Operational data was reviewed and analyzed for all five wells. The analysis plot for each well is  
13 included in the following list of figures:

- 14 • Operational data overview plots: Figures D-26 through D-32
- 15 • Operational pressure gradient plots: Figures D-33 through D-39
- 16 • Hall integral and derivative plot: Figures D-40 through D-46
- 17 • Silin slope plots: Figures D-47 through D-53
- 18 • Tandem plots: Figures D-54 through D-60

Table D-6 summarizes data associated with the Hall integral and Silin slope plot and compares the average pressure estimated for the Hall integral to the value determined from the corresponding Silin slope plot.

**TABLE D-6: CLEBURNE AREA HALL AND SILIN SLOPE PLOT RESULTS SUMMARY**

| Well                       | Assumed Average Pressure for Hall Plot (psia) | Calculated Average Pressure from Silin Slope Plot (psia) |
|----------------------------|---|--|
| Sparks SWD 1 (WDW-401)     | 3800  | 3875   |
| S. Mann SWD 1              | 3100  | 4642   |
| South Cleburne SWD 1       | 4730  | 4879   |
| Johnson Salty SWD Well II  | 3200  | 4048   |
| Johnson Salty SWD Well III | 3600  | 4002   |
| Cleburne Yard SWD 1        | 3530  | 4152   |
| Johnson County SWD 1       | 3600  | 4301   |

The operating pressure data analysis completed for each well is summarized below.

- Operational data overview plots (Figures D-26 through D-32)
- Operating pressure gradient plots (Figures D-33 through D-39):
  - Below 0.7 psi/ft rule of thumb fracture gradient in all wells
- Hall integral and derivative plot:
  - Sparks SWD 1 (Figure D-40)
    - A single negative slope break on Hall integral at approximately 1.1 MMbbls (June 2007)
    - Derivative stays below Hall integral until 2.49 MMbbls (April 2008)
  - S. Mann SWD 1 (Figure D-41)
    - Negative slope break on Hall integral at approximately 2.6 MMbbls (May 2007)
    - Derivative moves below Hall integral and remains below until approximately 21 MMbbls (Oct 2010)
  - South Cleburne SWD 1 (Figure D-42)
    - Negative slope break on Hall integral at approximately 3 MMbbls (June 2007)
    - Derivative moves below Hall integral and remains below through the remainder of the test
  - Johnson Salty SWD Well II (Figure D-43)
    - Normal injection behavior with some derivative scatter due to rate fluctuations
  - Johnson Salty SWD Well III (Figure D-44)

- Normal injection behavior with some derivative scatter due to rate fluctuations
- Cleburne Yard SWD 1 (Figure D-45)
  - Several negative slope breaks on Hall integral and derivative generally located below Hall integral after 1.16 MMbbls (February 2009)
- Johnson County SWD 1 (Figure C-46)
  - Two negative slope breaks on Hall integral at approximately 1 MMbbls (July 2007) and 12 MMbbls (July 2009)
- Silin slope plot:
  - Sparks Drive SWD 1 (Figure D-47)
  - S. Mann SWD 1 (Figure D-48)
  - South Cleburne SWD 1 (Figure D-49)
  - Johnson Salty SWD Well II (Figure D-50)
  - Johnson Salty SWD Well III (Figure D-51)
  - Cleburne Yard SWD 1 (Figure D-52)
  - Johnson County SWD 1 (Figure D-53)

The average reservoir pressures predicted by the slope plots were generally higher than the static pressure values assumed for the Hall integral plots. The difference may possibly be attributed to the well exhibiting slope breaks on the Hall plot.

- Tandem plot: (Figures D-54 through D-60)
  - Sparks Drive SWD 1 (Figure D-54)
    - No correlation observed
  - S. Mann SWD 1 (Figure D-55)
    - No correlation observed
  - South Cleburne SWD 1 (Figure D-56)
    - No correlation observed
  - Johnson Salty SWD Well II (Figure D-57)
    - Hall integral shift observed at 8.1 MMbbls (May 2009) corresponding to a series of earthquake events
  - Johnson Salty SWD Well III (Figure D-58)
    - Hall integral shift observed at a cumulative injection at approximately 8.3 MMbbls (May 2009) corresponding to a series of earthquake events
  - Cleburne Yard SWD 1 (Figure D-59)
    - Two series of earthquake events occur prior to two slope changes on the Hall plot
  - Johnson County SDW 1 (Figure D-60)
    - No correlation observed

## PRESSURE TRANSIENT TEST PLOTS AND OBSERVATIONS

Annual falloff test data for Sparks SWD 1 was analyzed using PanSystem® welltest software. Each test was plotted in a log-log format with the derivative response and then compared against various reservoir type curve models to identify flow regimes and reservoir and completion characteristics present. Data specific to each falloff test is summarized in Table D-7.

A summary of the Sparks Drive SWD 1 pressure transient test plot analyses are summarized in Table D-8 and additional discussion on select tests is included below:

- 2005 and 2006 falloff test
  - Overview plot (Figure D-61 and D-65)
    - 2005 pressure declining measurably (1.33 psi/hr) at the end of the test
    - 2006 pressure declining measurably (1.74 psi/hr) at the end of the test
  - Log-log plot (Figure D-62 and D-66)
    - 2005 and 2006 plots suggest a highly stimulated completion followed by a pressure derivative decline
    - 2006 – linear derivative added indicating linear flow during part of the test (Figure D-67)
  - Type curve match
    - 2005 Radial homogeneous type curve (Figure D-63)
      - Suggests a stimulated completion
      - Late time data deviated from the fracture type curve model
    - 2005 and 2006 Infinite conductivity fracture type curve (Figure D-64 and D-69)
      - Suggests high conductivity fracture
      - 2006 test yielded similar match results with both infinite and finite conductivity (Figure D-68) fracture type curves
    - 2006 test could be matched using only the early (Figure D-69) or late time (Figure D-70) portions of the tests
      - Overall test did not fit a single type curve model
      - Both early and late responses fit a fracture type curve model with similar fracture half length dimensions
      - Early response kh result was roughly twice late response kh value
- 2008 Falloff test
  - Overview plot (Figure D-71)
    - Pressure declining measurably (1.26 psi/hr) at the end of the test
  - Log-log plot (Figure D-72)
    - Linear flow behavior followed by late time derivative decline

- Type curve
  - Radial homogeneous type curve (Figure D-73)
    - Suggests a stimulated completion
  - Infinite conductivity fracture type curve (Figure D-74)
    - Highly conductive fracture with results similar to 2005 and 2006 falloff tests
- 2009 Falloff test
  - Overview plot (Figure D-75)
    - Pressure declining measurably (0.82 psi/hr) at the end of the test
  - Log-log plot (Figure D-76)
    - Late time data shows a derivative decline with a negative half slope
      - Possibly indicating spherical flow/layering
  - Dual permeability type curve (Figure D-77)
    - Late time portion of test fit a two layer model
- 2010 Falloff test
  - Overview plot (Figure D-78)
    - Pressure declining measurably (2.45 psi/hr) at the end of the test
  - Log-log plot (Figure D-79)
    - Linear flow with late time derivative decline
  - Type curve
    - Infinite conductivity fracture type curve (Figure D-80)
      - Highly conductive fracture similar to 2005, 2006 and 2009 falloff tests
    - Dual Permeability type match with late time data only (Figure D-81)
      - Late time portion of test fit a two layer model
- 2011 Falloff test
  - Overview plot (Figure D-82)
    - Pressure declining measurably (3.38 psi/hr) at the end of the test
  - Log-log plot (Figure D-83)
    - Highly stimulated completion
  - Type curve (Figure D-84)
    - Infinite conductivity fracture type curve
      - Marginal match with a highly conductive fracture similar to 2005, 2006, 2009, and 2010 tests

TABLE D-7: SPARKS DRIVE SWD 1 (WDW 401) FALLOFF TEST CONDITIONS

| Test Date | Injection Time (hrs) | Shut-in Time (hrs) | Gauge Depth (ft KB) | Final Injection Pressure (psia) and Rate (gpm) | Final Shut-in Pressure (psia) and Pressure Decline Rate (psi/hr) |
|-----------|----------------------|--------------------|---------------------|--|--|
|-----------|----------------------|--------------------|---------------------|--|--|

|              |       |       |      |               |                |
|--------------|-------|-------|------|---------------|----------------|
| 8/29-30/2005 | 30.12 | 18.7  | 7620 | 4189.33/ 156  | 3851.12 / 1.33 |
| 9/21-22/2006 | 16    | 20.5  | 5500 | 3361.79/ 173  | 2921.68/ 1.74  |
| 8/25-26/2008 | 13.17 | 21.25 | 7500 | 4227.07/ 215  | 3859.42/ 1.26  |
| 8/27-28/2009 | 124.2 | 21.18 | 6334 | 3781.70/ 128  | 3281/ 0.82     |
| 8/4-5/2010   | 18.5  | 20    | 7620 | 4252.49/ 95.5 | 3876.98/ 2.45  |
| 8/1-2/2011   | 240   | 20.2  | 7620 | 4316.90/ 99   | 3973.69/ 3.38  |

## SPARKS DRIVE SWD 1 (WDW-401) FALLOFF TESTS SUMMARY

Tests generally indicated a fractured or highly stimulated completion signature, but entire test responses did not fit a simple model. Early time test responses were fitted to type curve models while the late time portions of the test deviated from the type curve response.

Late time test behaviors indicated pressure support/communication in the form of a declining pressure derivative response. This could reflect communication with a pressure support source, such as another layer. Two of the late time test responses fit a dual permeability (two layer) type curve model.

Type curve matches were marginal, but all indicated a highly stimulated completion with matches obtained using both homogeneous reservoir and infinite conductivity fracture type curves to match the early portions of several falloffs. As the Ellenburger formation is naturally fractured, this type of response is consistent.

Matches also indicated a moderate transmissibility interval with transmissibilities in the 4,000-15,000 md-ft/cp range. Fracture characteristics from the type curve matches fit an unproppped fracture with fracture wing lengths on the order of 160 to 250 feet long.

The falloffs did not reach static pressure conditions at test end time as all the falloffs displayed noticeable pressure declines at their conclusions.

**TABLE D-8: CLEBURNE AREA FALLOFF TEST ANALYSIS RESULTS**

| Test | Type Curve Model               | kh/u (md-ft/cp) | Skin Factor | $x_f$ (ft) | Comments              |
|------|--------------------------------|-----------------|-------------|------------|-----------------------|
| 2005 | Homogeneous                    | 3633            | -5.3        | ---        |                       |
|      | Infinite Conductivity Fracture | 3287            | -5.7        | 200        |                       |
| 2006 | Finite Conductivity Fracture   | 10,380          | -4.5        | 190        |                       |
|      | Infinite Conductivity Fracture | 10,380          | -4.5        | 160        | Early time data match |
|      | Infinite Conductivity Fracture | 4325            | -5.6        | 170        | Late time data match  |

|      |                                |        |      |     |                               |
|------|--------------------------------|--------|------|-----|-------------------------------|
| 2008 | Homogeneous                    | 13,107 | -5.3 |     |                               |
|      | Infinite Conductivity Fracture | 12,317 | -5.4 | 176 |                               |
| 2009 | ---                            | ---    | ---  | --- | Not quantitatively analyzable |
| 2010 | Infinite Conductivity Fracture | 2595   | -5.6 | 175 |                               |
| 2011 | Infinite Conductivity Fracture | 4556   | -5.5 | 254 |                               |

1

## 2 ACTIONS TAKEN BY UIC REGULATORY AGENCY IN THE NORTH TEXAS CLEBURNE AREA

3 Following the seismic events, the RRC worked with the operator of the nearest disposal well,  
4 Chesapeake Operating, Inc.'s: *South Cleburne SWD 1*. Chesapeake voluntarily shut the well in,  
5 though they do not consider the evidence to be conclusive. The RRC reviewed its permit  
6 actions for this wells, as well as other wells in the area in an effort to determine if the activity  
7 could have been predicted. No indications of possible induced seismicity were found in these  
8 reviews. RRC also inspected the area to verify no measurable harm or potential hazard related  
9 to the events. In follow-up, the RRC consulted with industry representatives, and researchers  
10 at the Texas Bureau of Economic Geology, Southern Methodist University, and Texas A&M  
11 University, and continues to monitor developments and research related to induced seismicity.

## 12 REFERENCES

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- 14 Bruner, K. R., and Smosna, R., 2011, A comparative study of the Mississippian Barnett Shale,  
15 Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin: US Department of  
16 Energy, National Energy Technology Laboratory.
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18 Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.
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22 AAPG Bulletin, v. 91, no. 4, p. 399-403.
- 23 McDonnell, A. et al., 2007, Quantifying the origin and geometry of circular sag structures in  
24 northern Forth Worth Basin, Texas: Paleocave collapse, pull-apart fault systems, or  
25 hydrothermal alteration?: AAPG Bulletin, v. 91, no. 9, p. 1295-1318.
- 26 Montgomery, S. L. et al., 2005, Mississippian Barnett Shale, Fort Worth Basin, northcentral  
27 Texas: Gas-shale play with multi-trillion cubic foot potential: AAPG Bulletin, v. 89, no. 2,  
28 p. 155-175.
- 29 NEIC: <<http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>>

- 1 Steward, D. B., 2011, The Barnett Shale oil model of North Texas, Article #110151, Search and
- 2 Discovery, American Association of Petroleum Geologists/Datapages, Inc.

DRAFT



**Earthquakes through 01/31/2012**

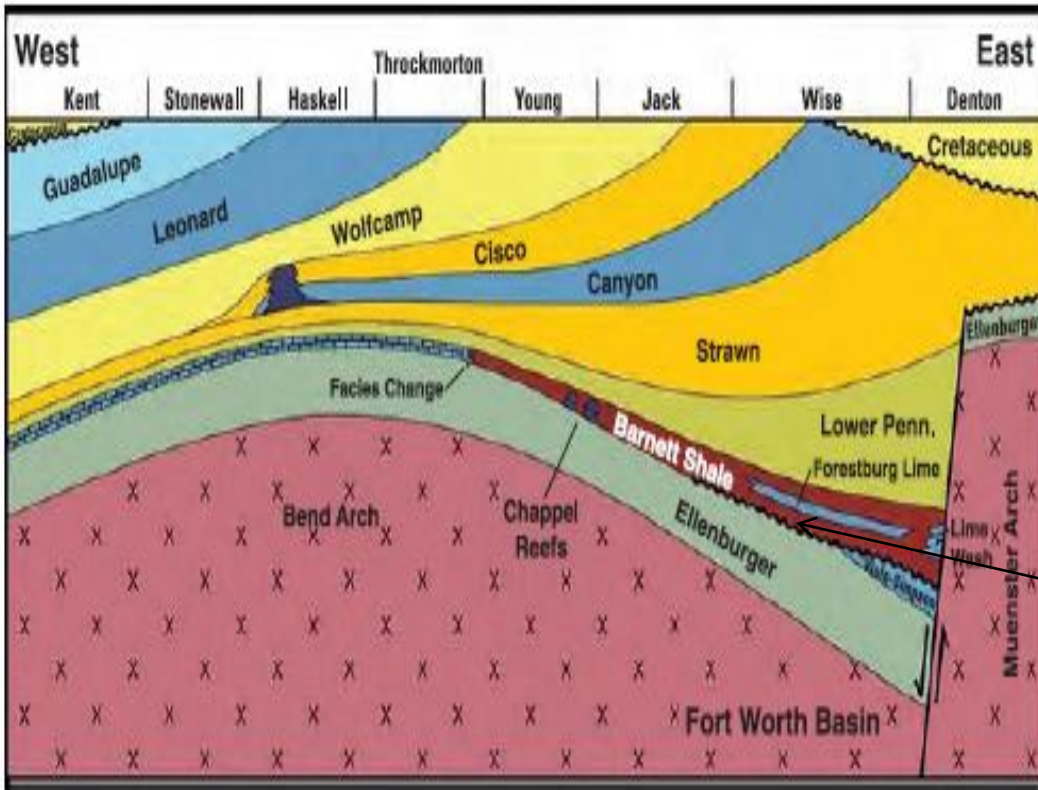
If legend item, does not show in map, it is not in the area.

| Magnitude      | Earthquake Year | Seismometers         | Wells                     | Horizon: Top Ellenburger (Pollastro, 2007) |
|----------------|-----------------|----------------------|---------------------------|--|
| • No Magnitude | 2012            | ▲ <all other values> | ● Injection/Disposal Well | — Structure Contours                       |
| ★ 0 - 3        | 2009            | ▲ Ended              | ● Wells of Interest       | — Faults                                   |
| ★ 3.1 - 5      | 2011            | ▲ Operating          | ● Commercial Inj          |  |
| ★ 5.1 - 6      | 2010            |                      |                           |  |
|                | <2008           |                      |                           |  |

Compiled by:  
Nancy Dorsey, EPA R6

Compiled by:  
Nancy Dorsey, EPA R6

**FIGURE D-2: BARNETT SHALE, E-W GENERALIZED CROSS-SECTIONS (DOE)**

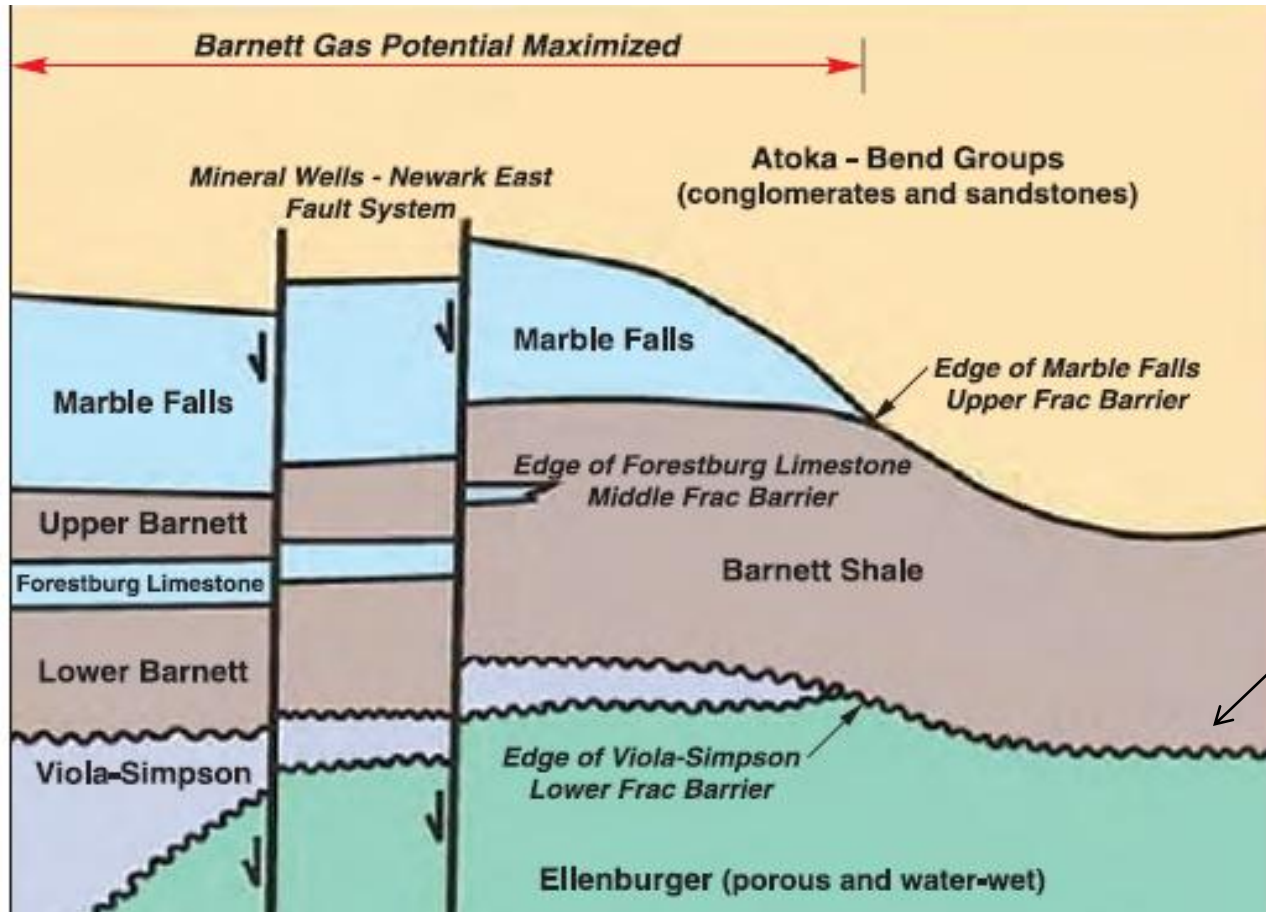


Barnett shale overlying the  
Ellenburger formation

**FIGURE D-3: BARNETT SHALE, N-S GENERALIZED CROSS-SECTIONS (DOE)**

North

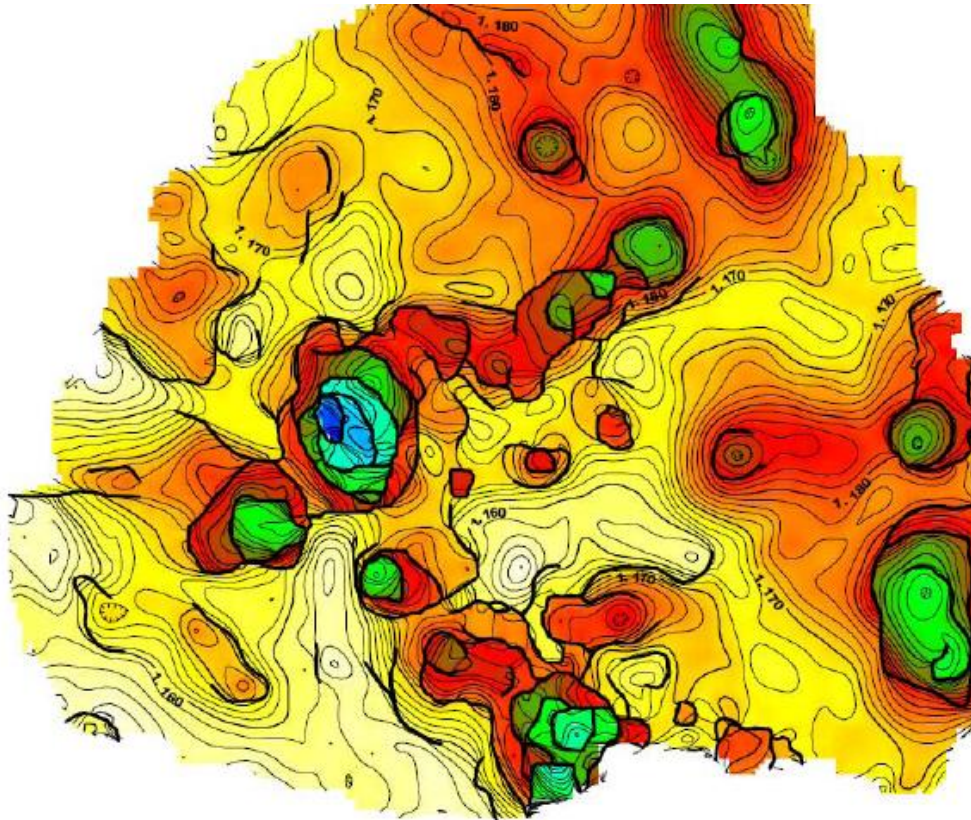
South



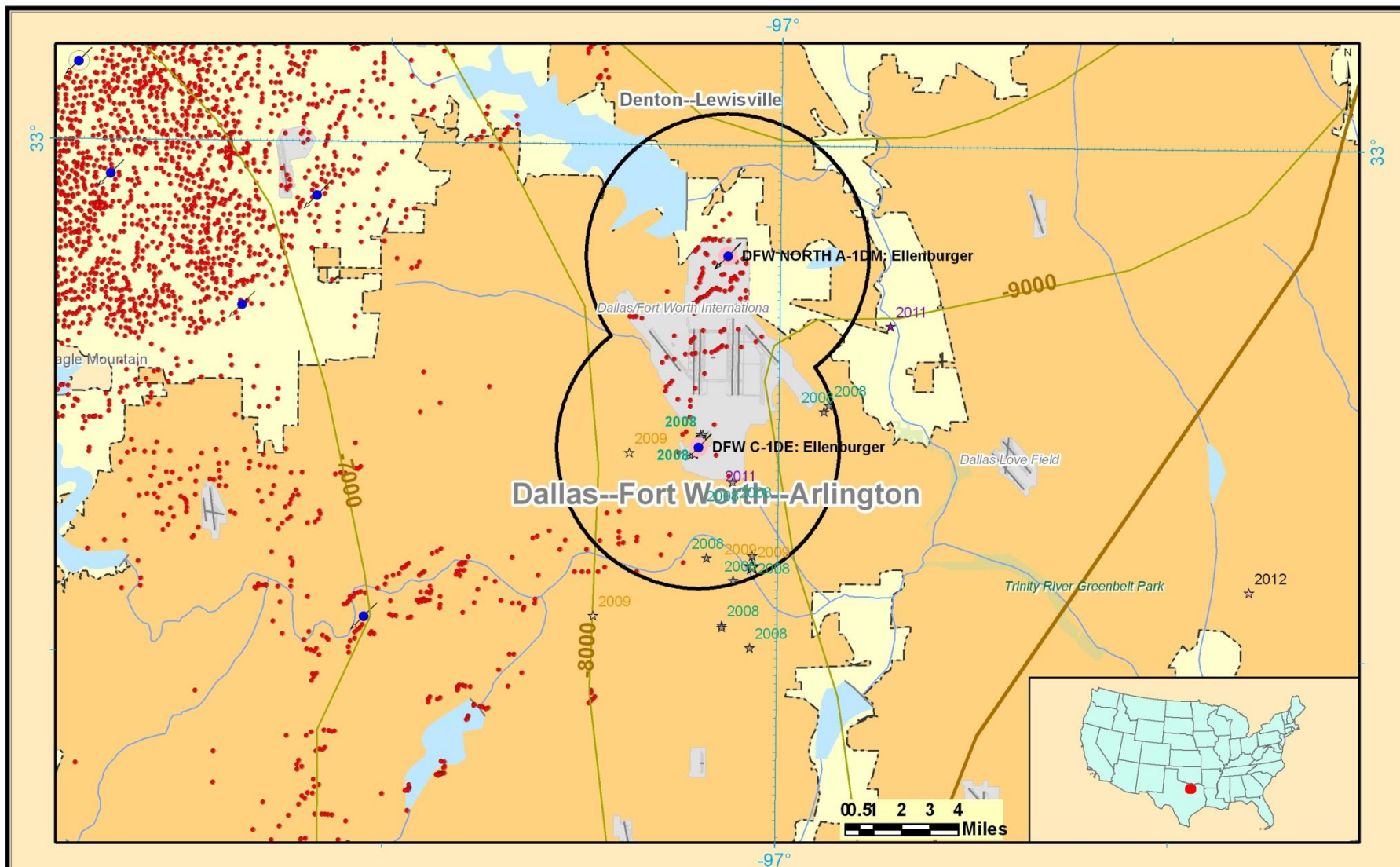
Barnett shale overlying the Ellenburger formation



**FIGURE D-4: TOP ELLENBURGER KARST FEATURES FROM 3D  
(USED BY PERMISSION OF REPUBLIC ENERGY)**



# FIGURE D-5: DFW INTERNATIONAL AIRPORT AREA SEISMICITY & WELL LOCATION MAP



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**

- No Magnitude
- ★ 0 - 3
- ★ 3.1 - 5
- ★ 5.1 - 6

**Earthquake Year**

|      |       |
|------|-------|
| 2012 | 2009  |
| 2011 | 2008  |
| 2010 | <2008 |

**Seismometers**

- △ <all other values>
- △ Ended
- ▲ Operating
- Wells of Interest

**Wells**

- Injection/Disposal Well
- Gas Well
- Oil Well
- Commercial Inj

**Horizon: Top Ellenburger (Pollastro, 2007)**

- Structure Contours
- Faults

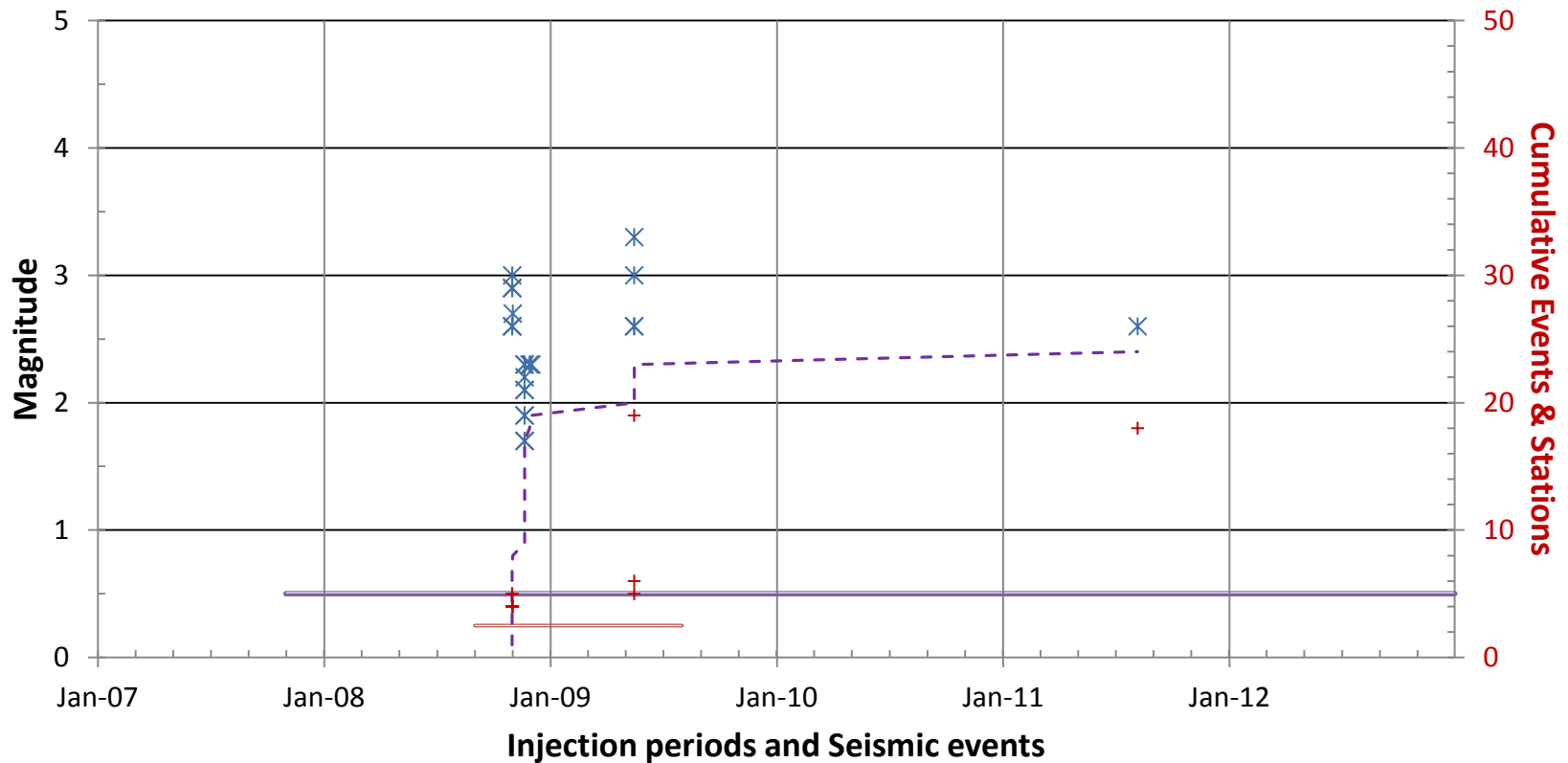
Oil and Gas wells at end of 2010

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

**FIGURE D-6: DFW AIRPORT AREA SEISMICITY AND INJECTION TIMELINE**

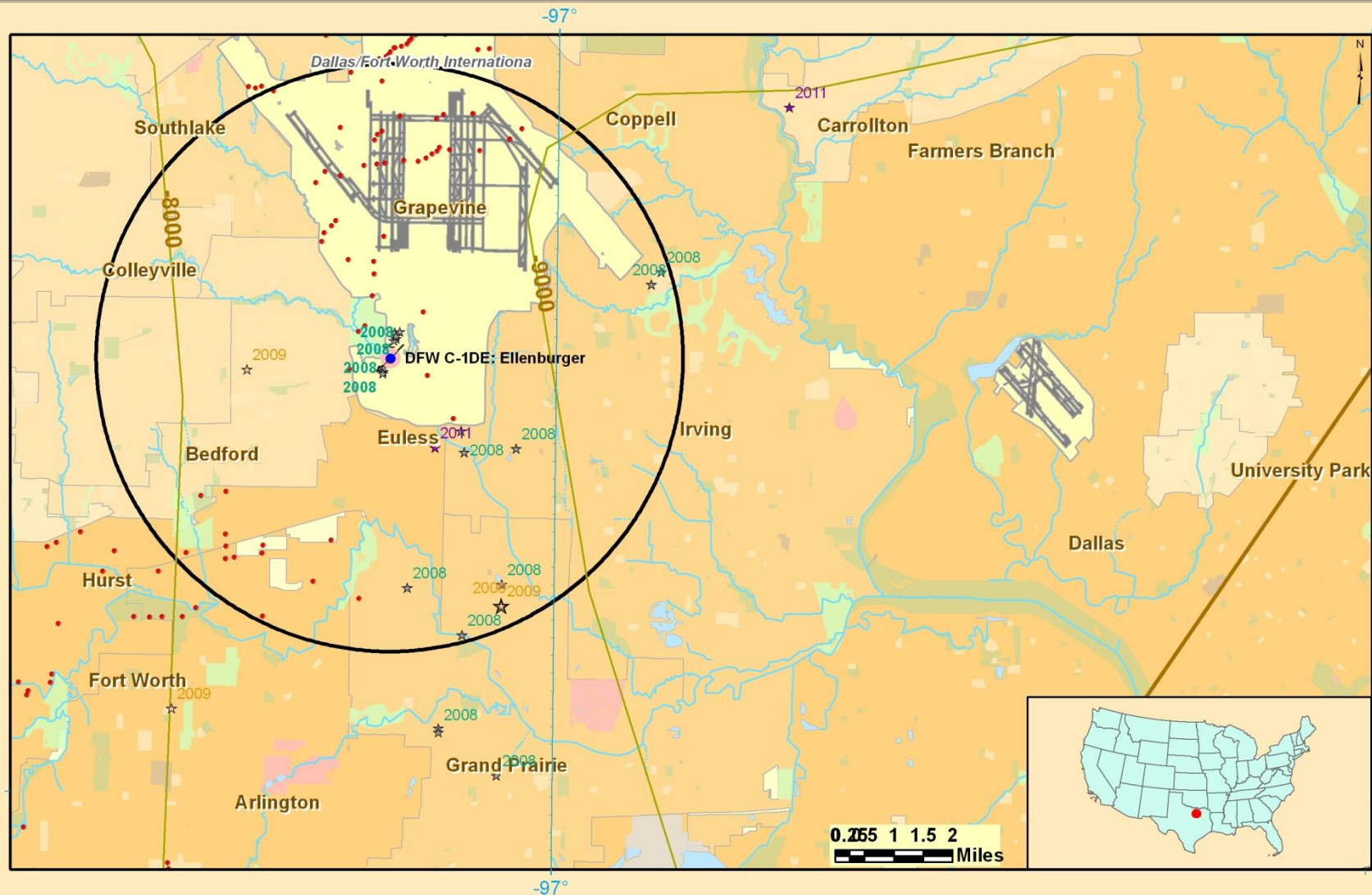
**DFW Seismicity**



× Event Magnitude    — DFW C-1DE    — DFW North A-1DM    - - - Cum Events in 5 mi.    + Nearby Stations



# FIGURE D-7: SEISMICITY WITHIN 5 MILE RADIUS DFW C1DE DISPOSAL WELL



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**  
 \* No Magnitude  
 ★ 0 - 3  
 ★ 3.1 - 5  
 ★ 5.1 - 6

**Earthquake Year**  
 2012  
 2011  
 2010  
 2009  
 2008  
 <2008

**Seismometers**  
 ▲ <all other values>  
 ▲ Ended  
 ▲ Operating  
 ● Wells of Interest

**Wells**  
 ● Injection/Disposal Well  
 ● Gas Well  
 ● Oil Well  
 ● Commercial Inj

**Horizon: Top Ellenburger (Pollastro, 2007)**

— Structure Contours  
 — Faults

Oil and Gas wells at end of 2010

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

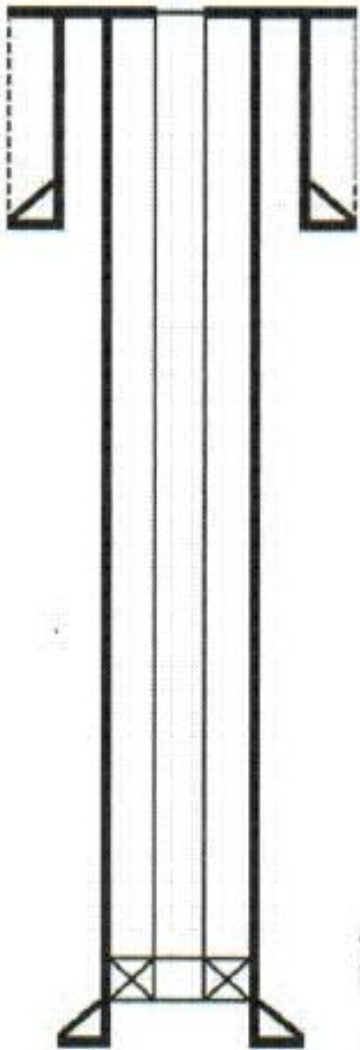
**FIGURE D-8: DFW AREA C1DE WELL SCHEMATIC**

**DFW #C1DE**  
**Well Bore Diagram**

**Conductor:**  
None

**Surface Casing:**  
10 3/4" @ 1,900'  
Cement Back to surface  
13 1/2" Hole

**Production Casing:**  
7" @ 10,047'  
Cement Back to surface  
9 7/8" Hole



4 1/2" Tubing  
Packer Set @ 9,997'

Disposal Interval  
10047 - 14375  
Open Hole

TD - 14,375



**FIGURE D-9: DFW C1DE OPERATING DATA OVERVIEW PLOT**

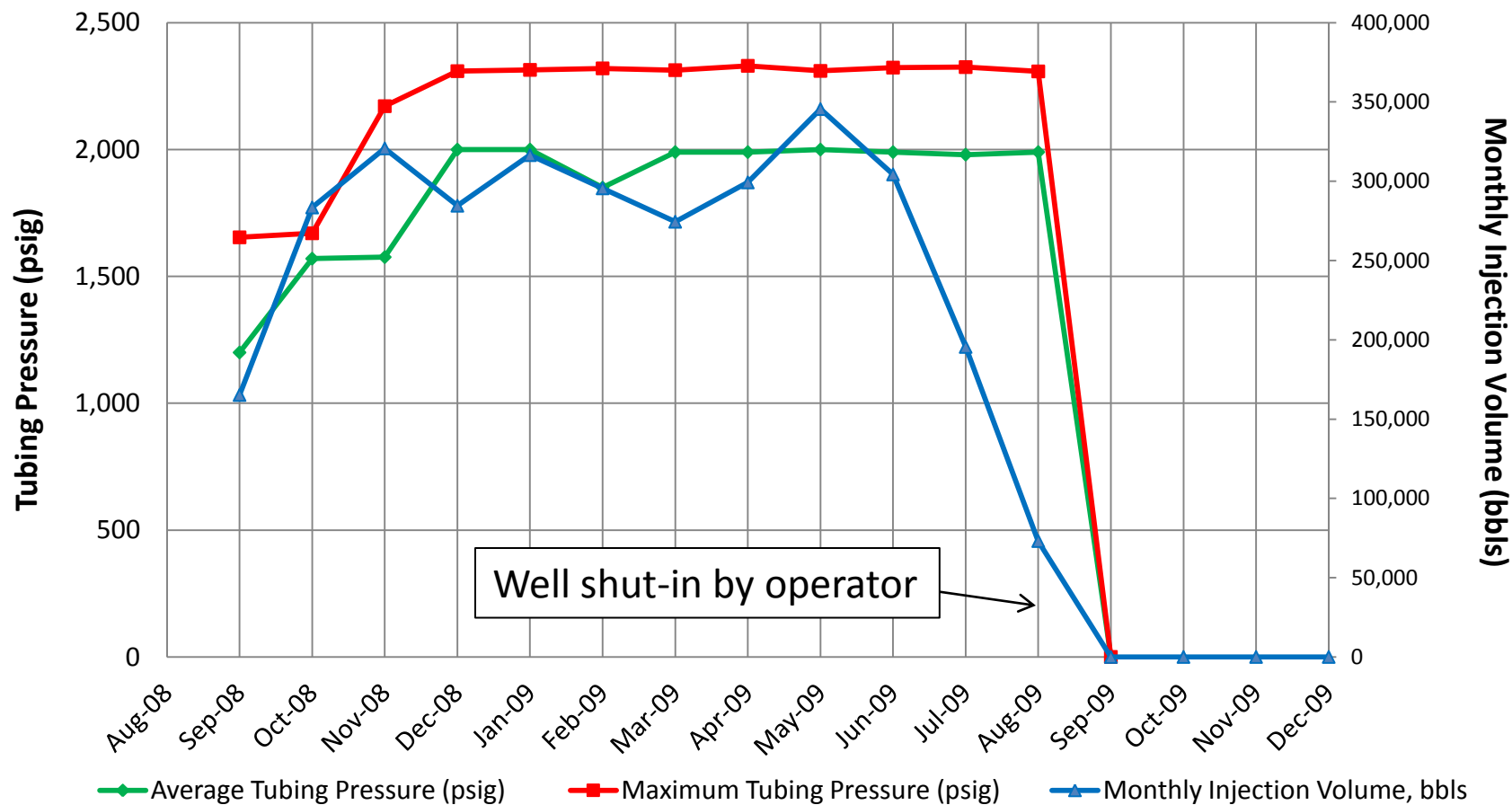


FIGURE D-10: DFW NORTH A1DM OPERATING OVERVIEW PLOT

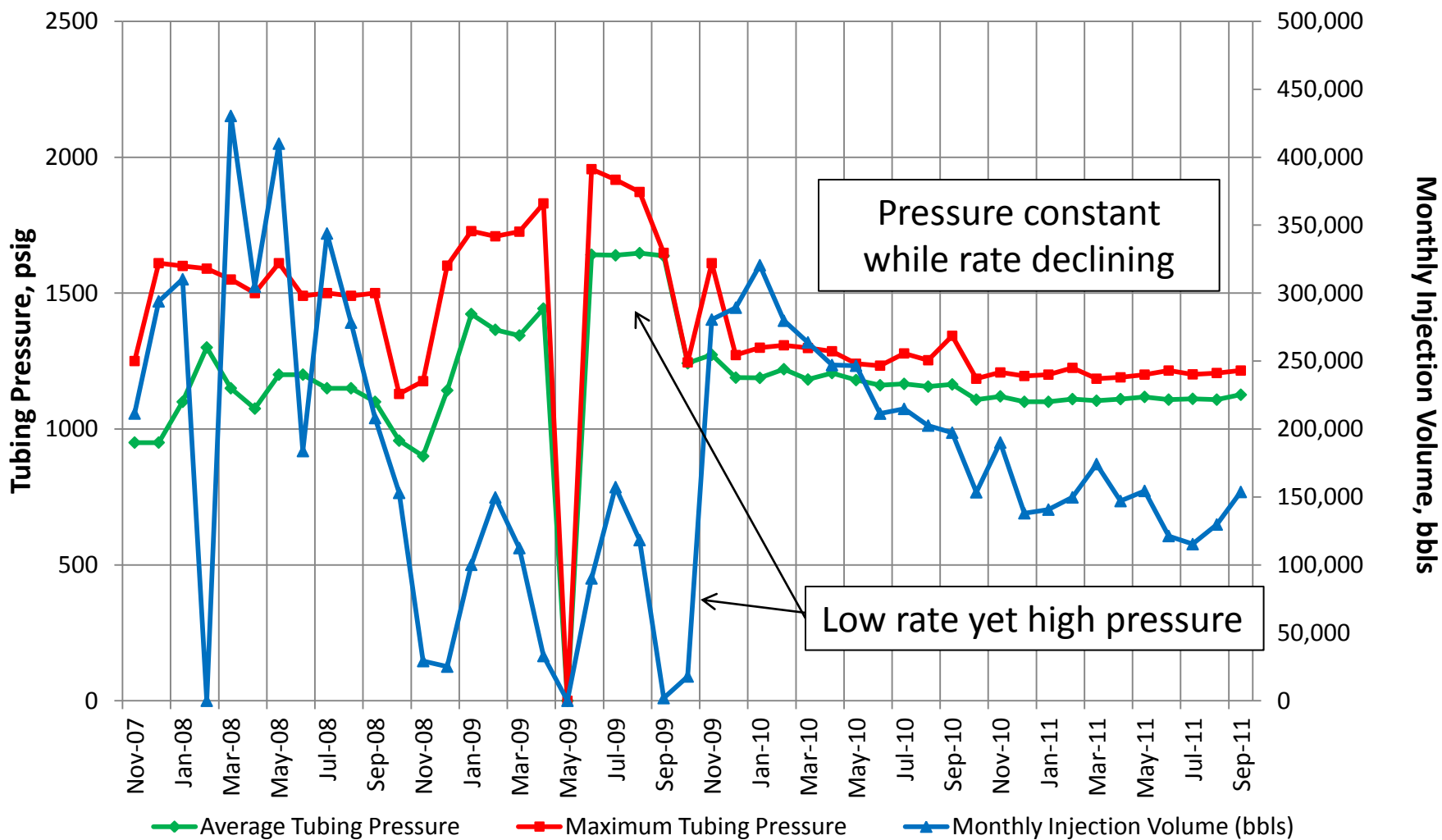


FIGURE D-11: DFW C1DE OPERATING PRESSURE GRADIENT

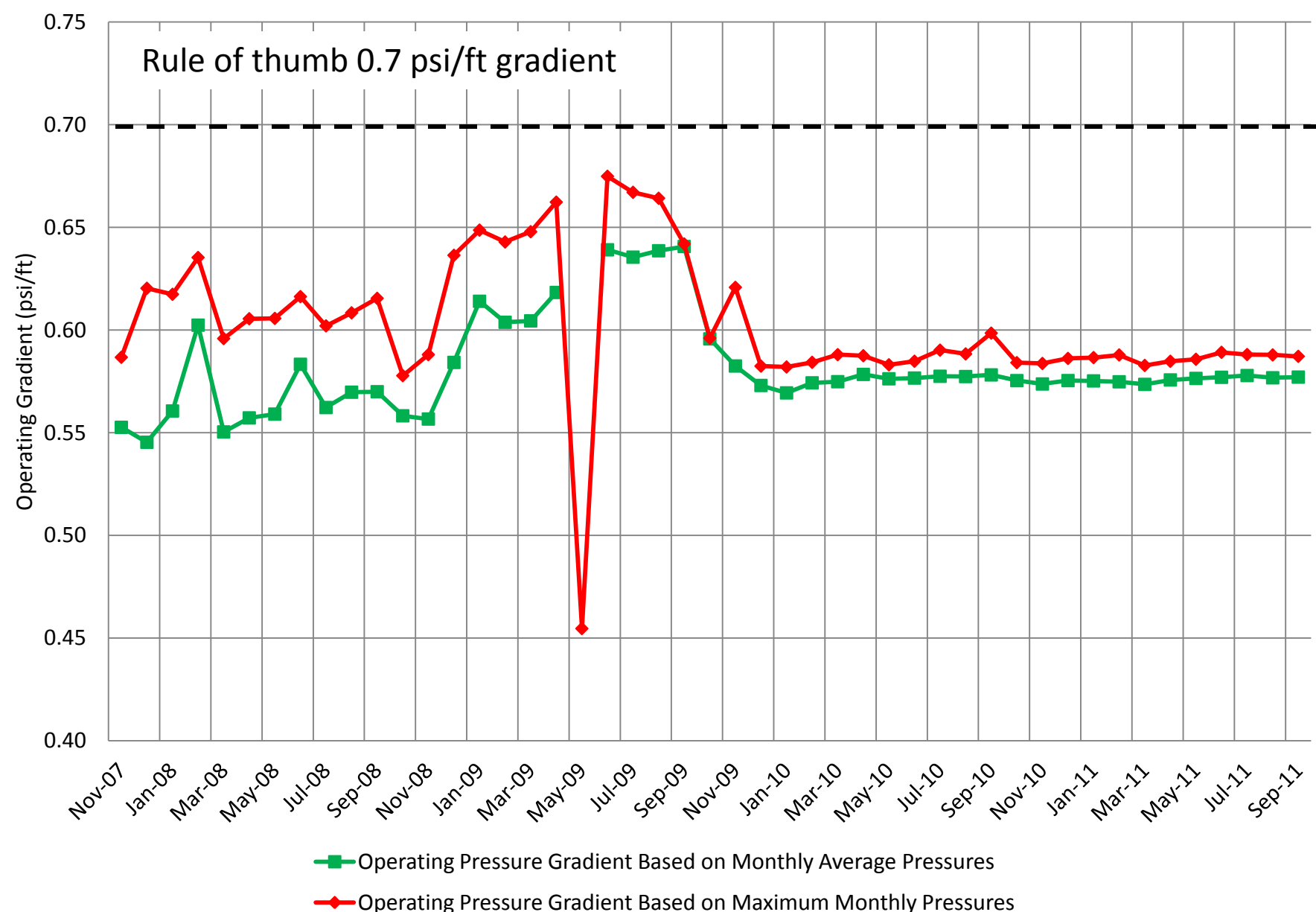
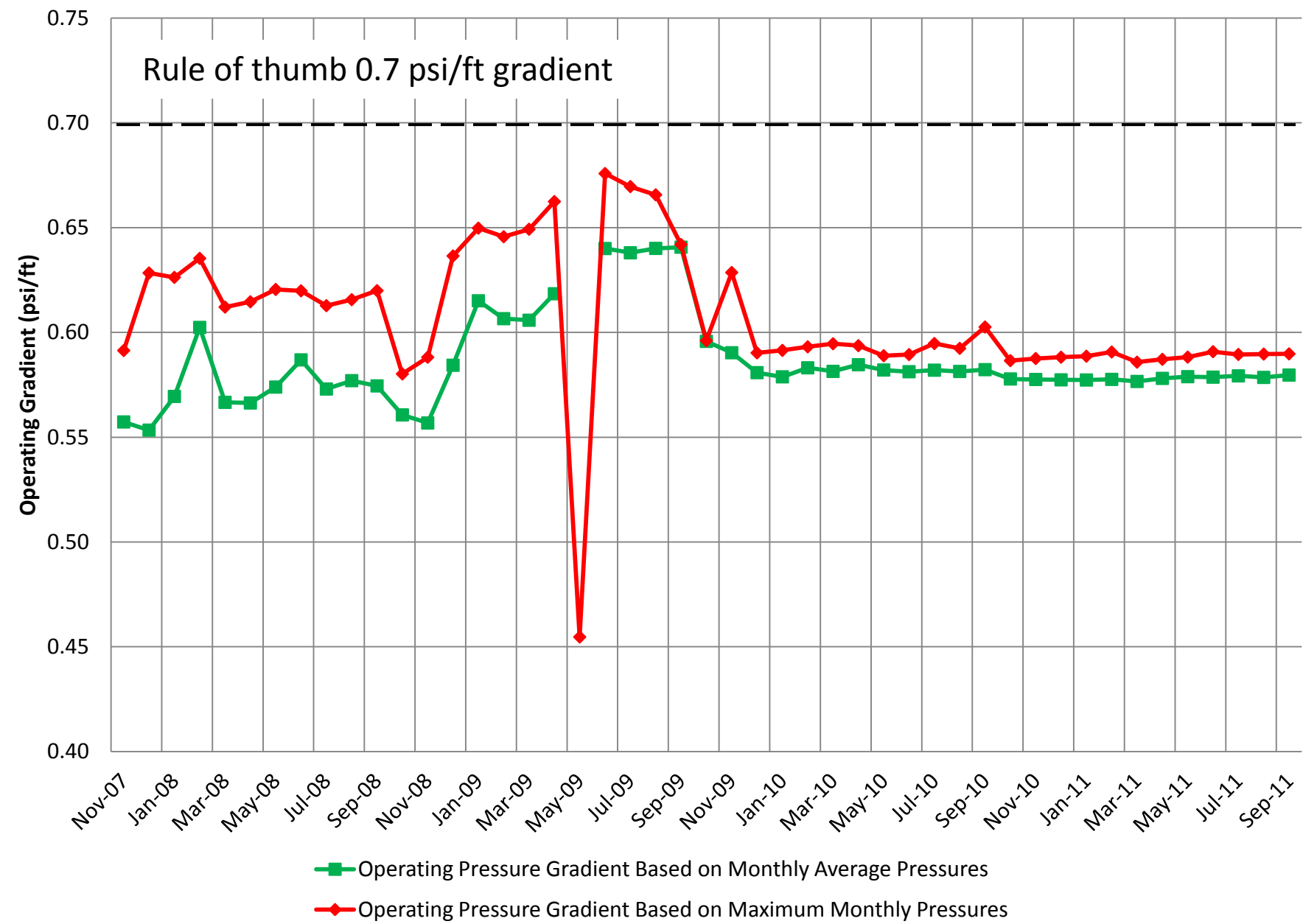
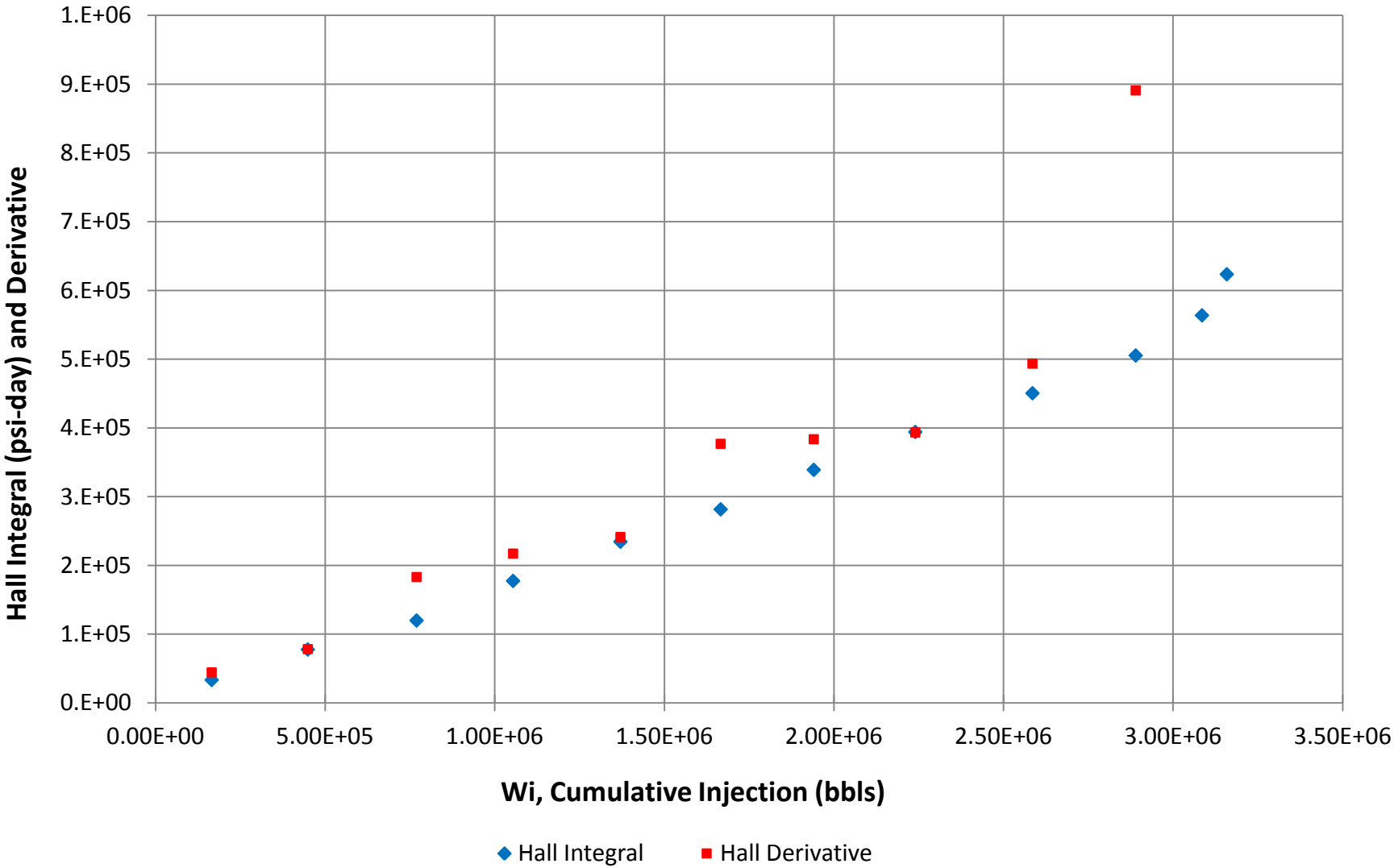


FIGURE D-12: DFW NORTH A1DM OPERATING PRESSURE GRADIENT



**FIGURE D-13: DFW C1DE HALL PLOT WITH DERIVATIVE**



**FIGURE D-14: DFW NORTH A1DM HALL PLOT WITH DERIVATIVE**

DFW Area North A1DM Hall Plot and Derivative

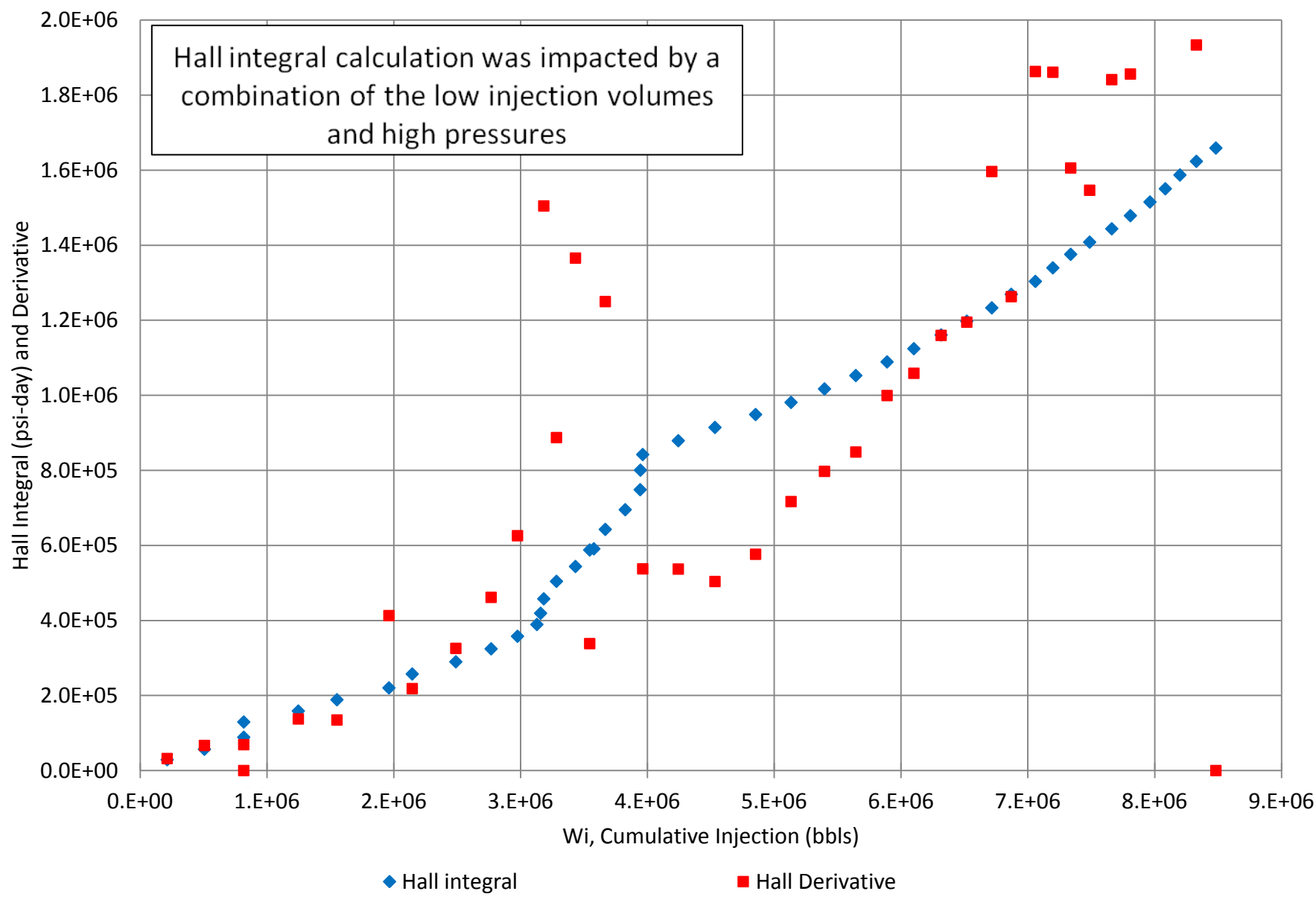
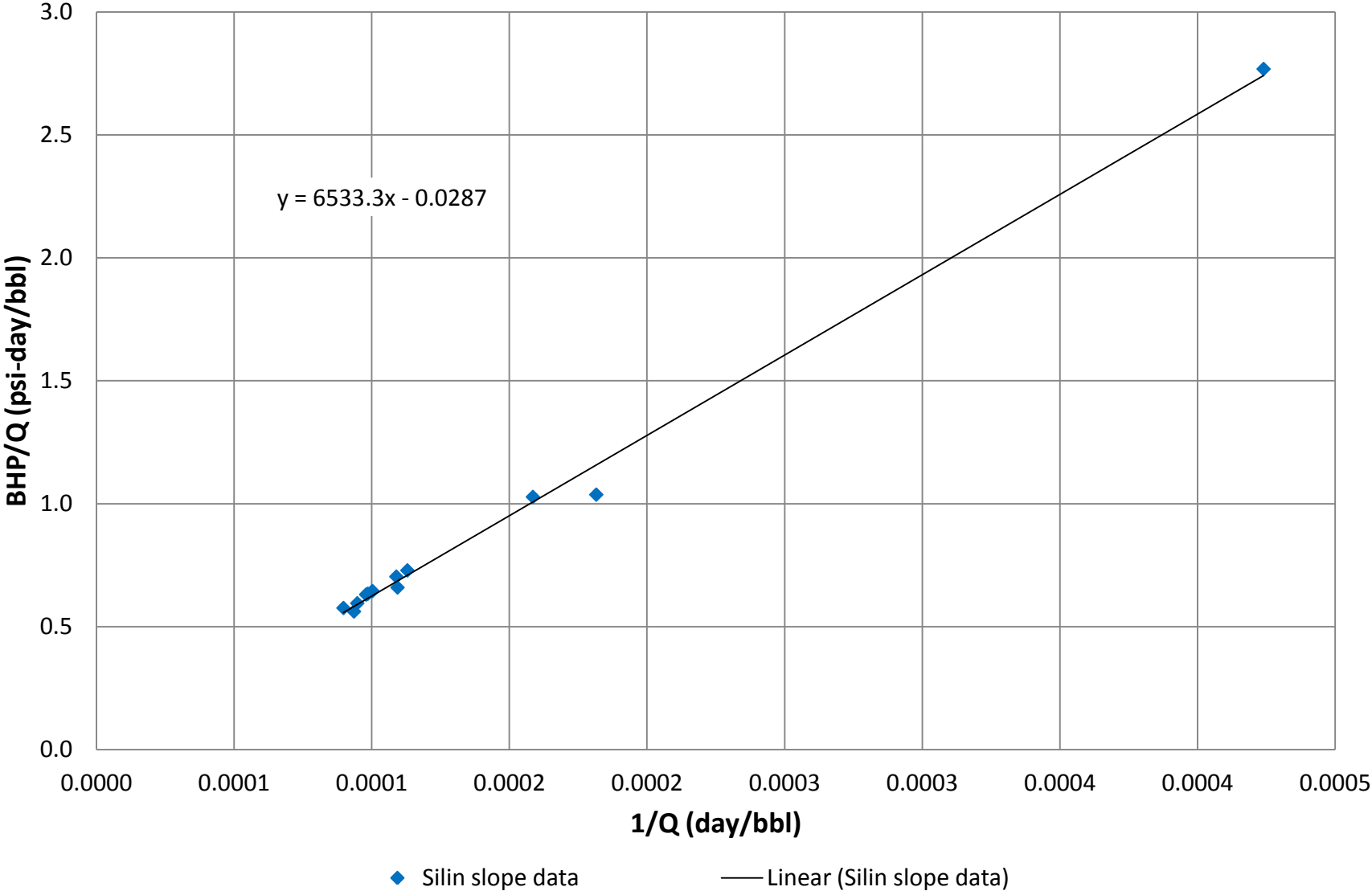
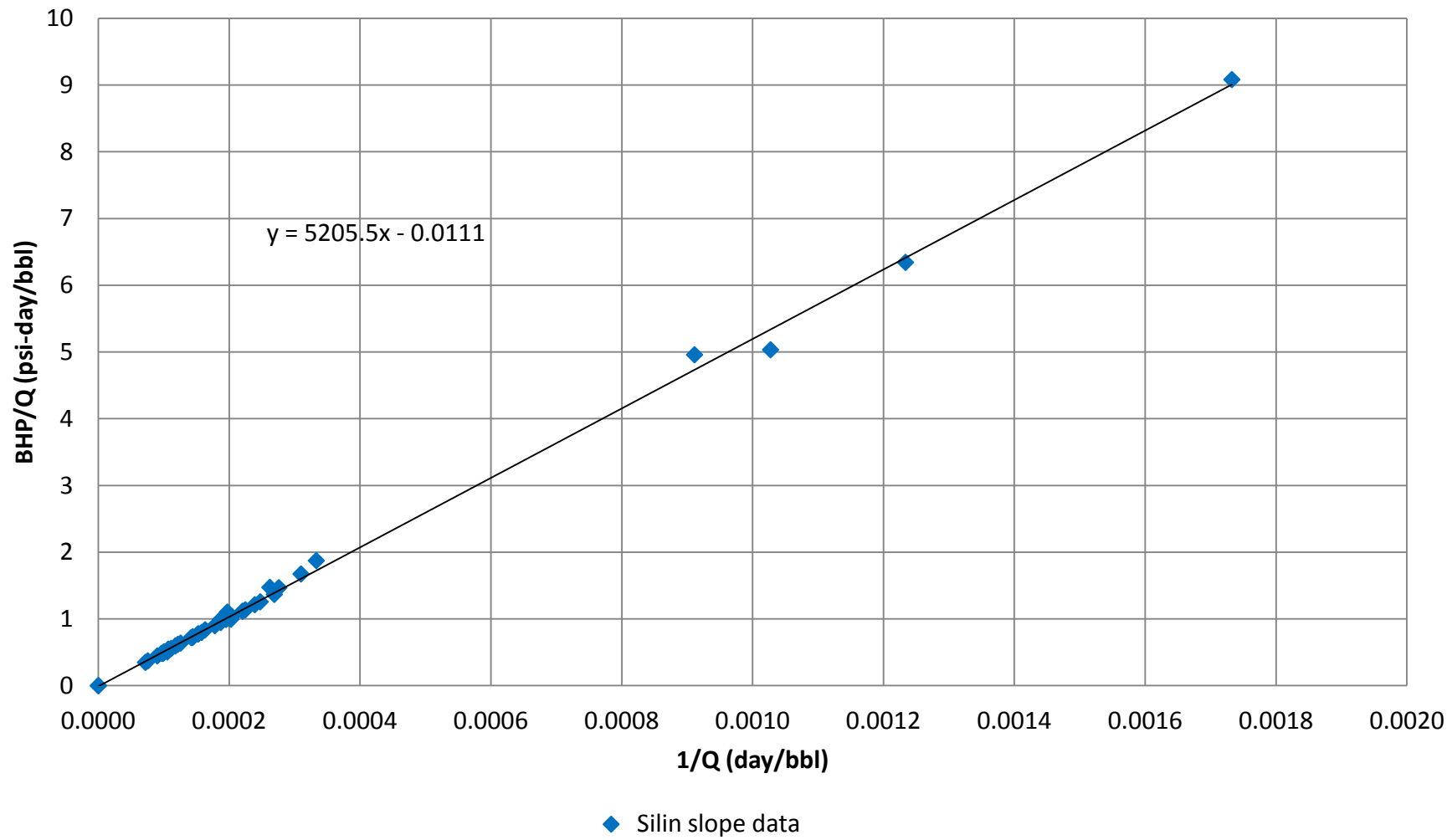


FIGURE D-15: DFW C1DE SILIN SLOPE PLOT



**FIGURE D-16: DFW NORTH A1DM SILIN SLOPE PLOT**





**FIGURE D-17: DFW C1DE TANDEM PLOT**

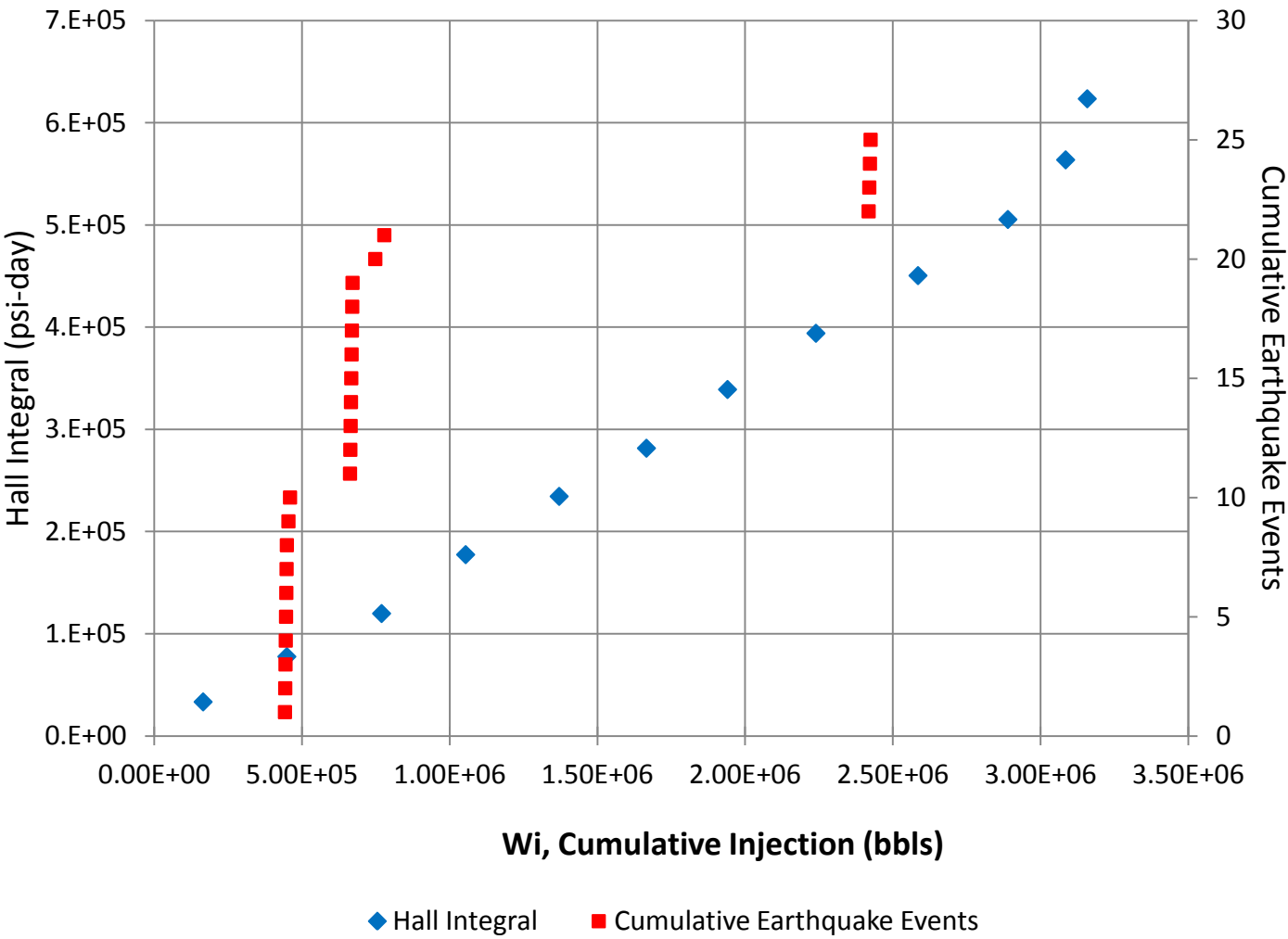
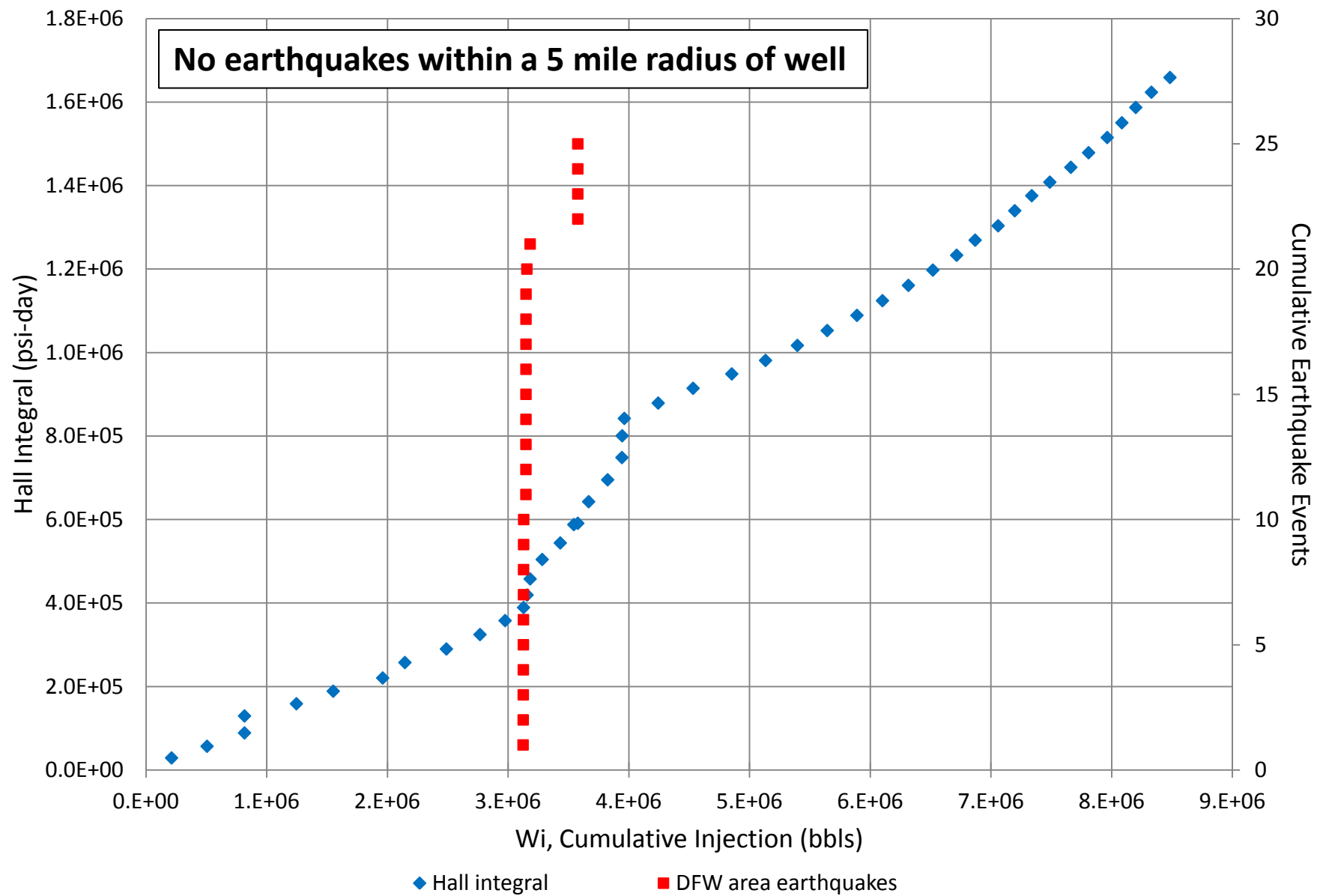
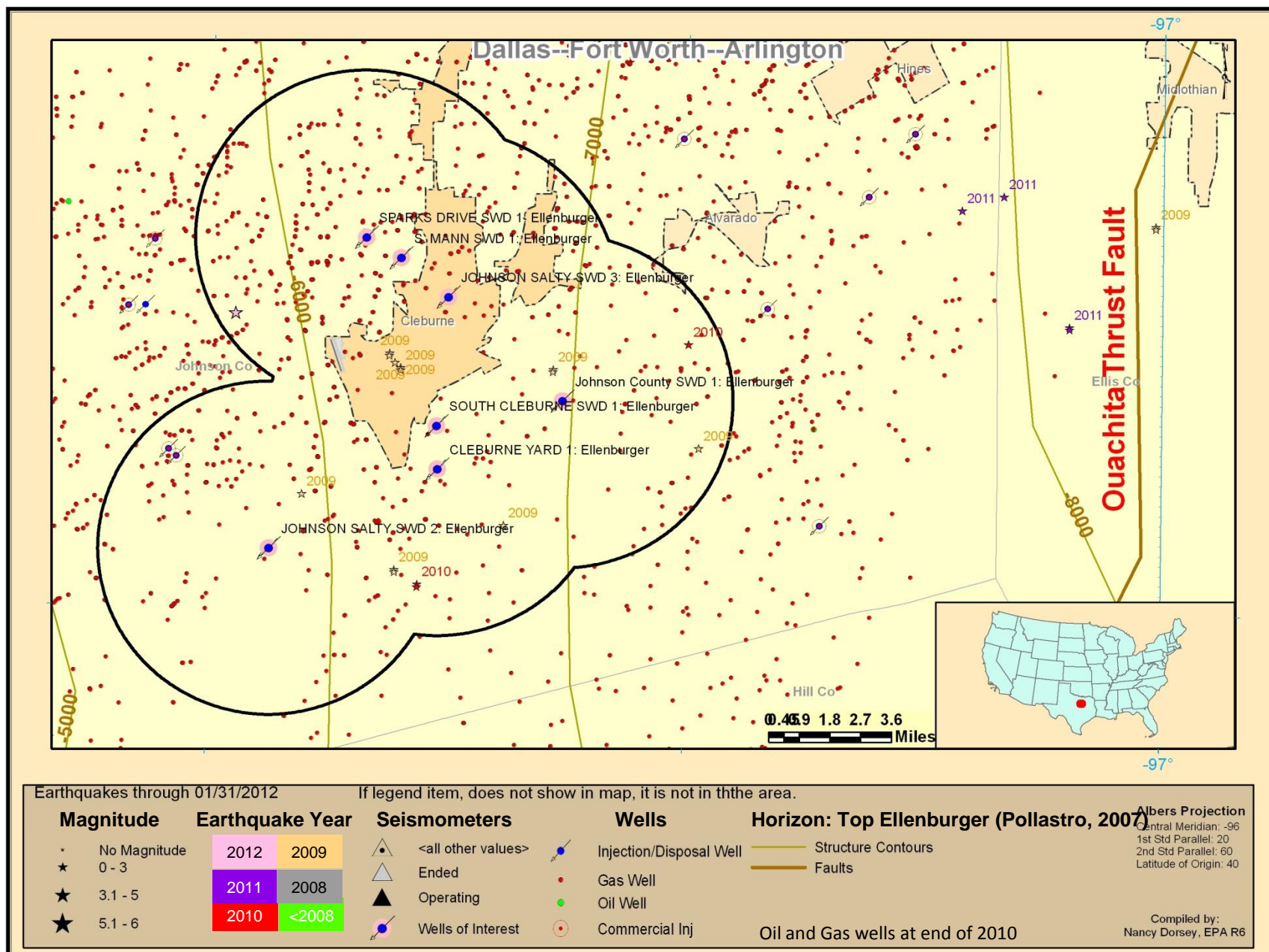


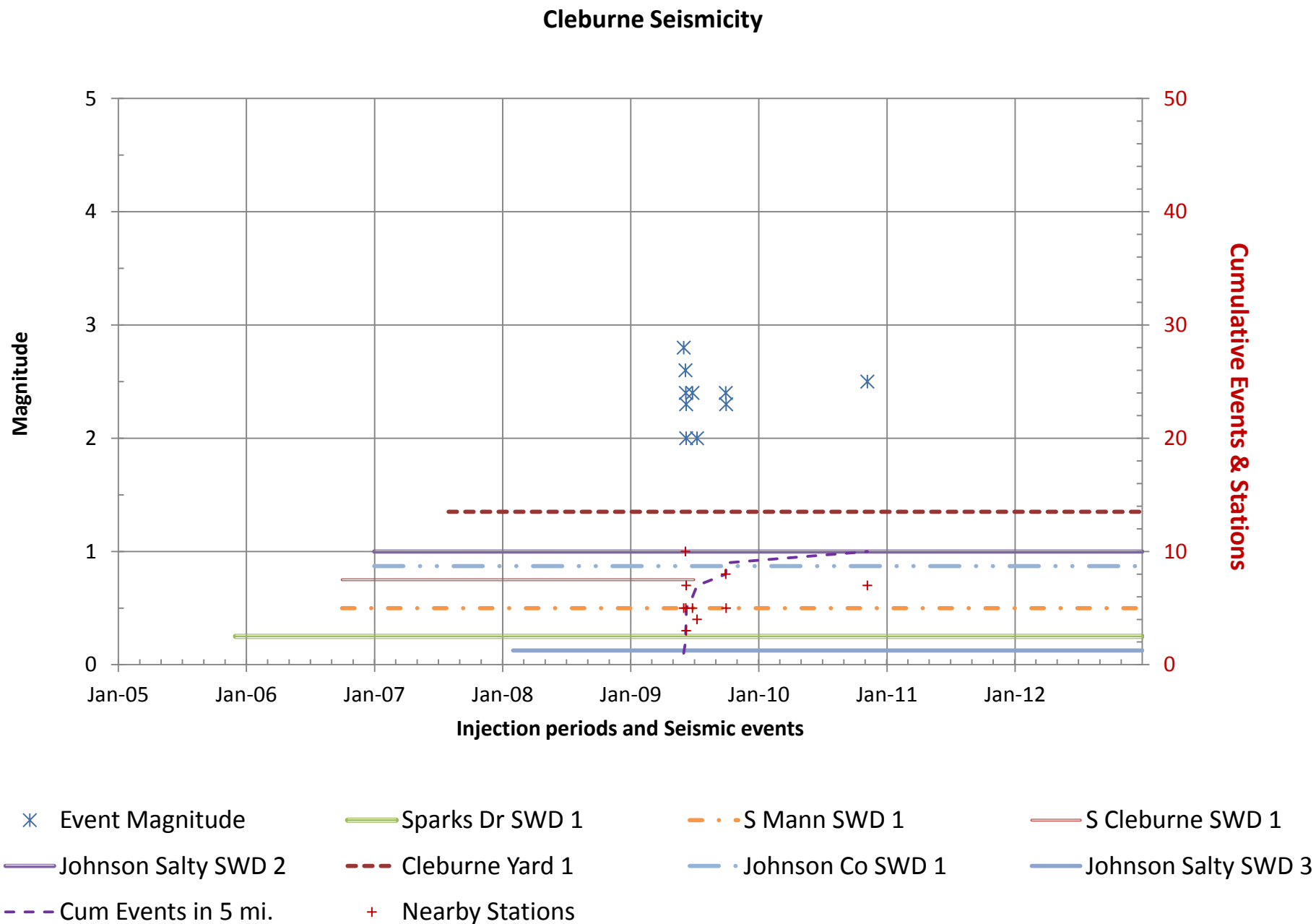
FIGURE D-18: DFW NORTH A1DM TANDEM PLOT



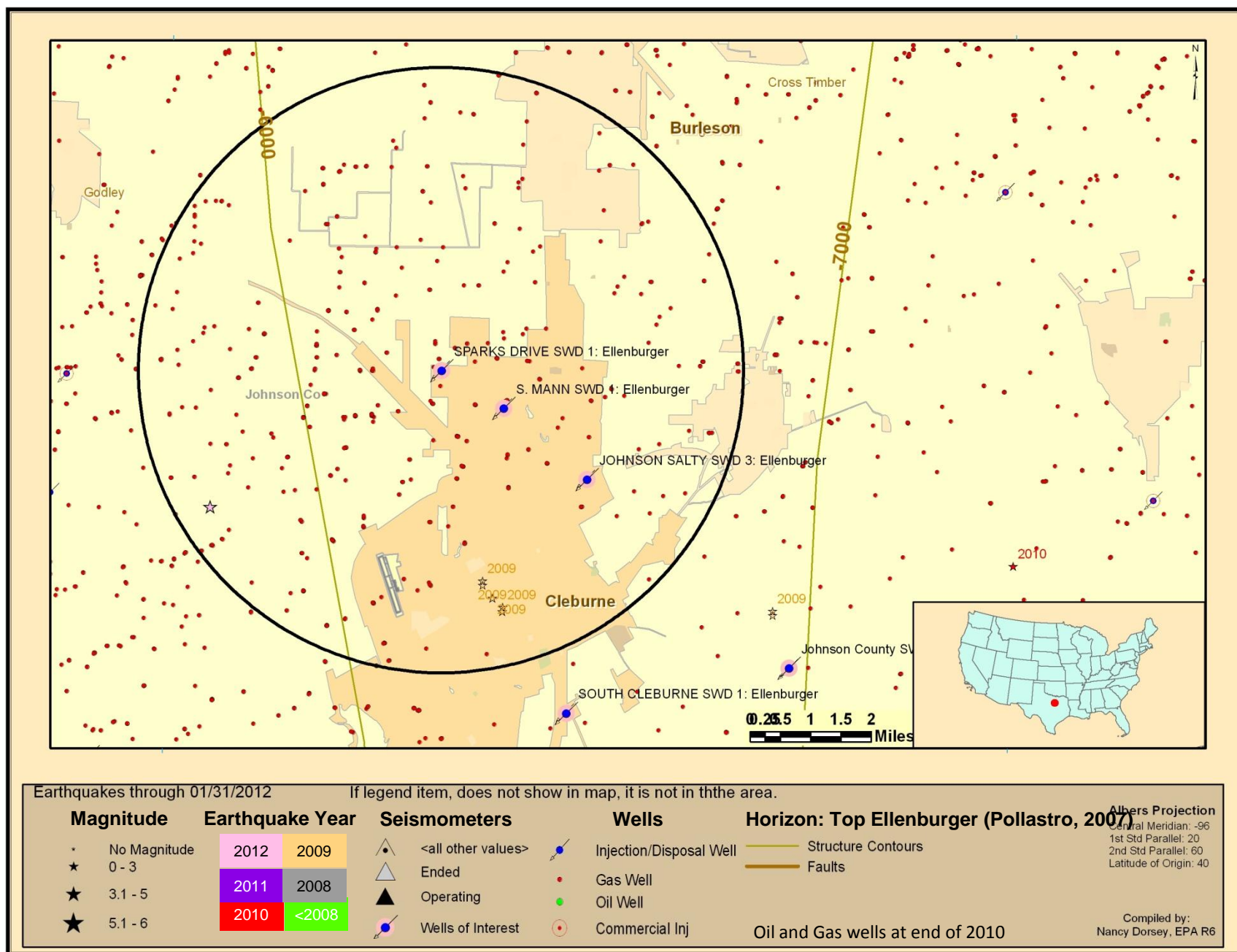
# FIGURE D-19: CLEBURNE AREA SEISMICITY & WELL LOCATION MAP



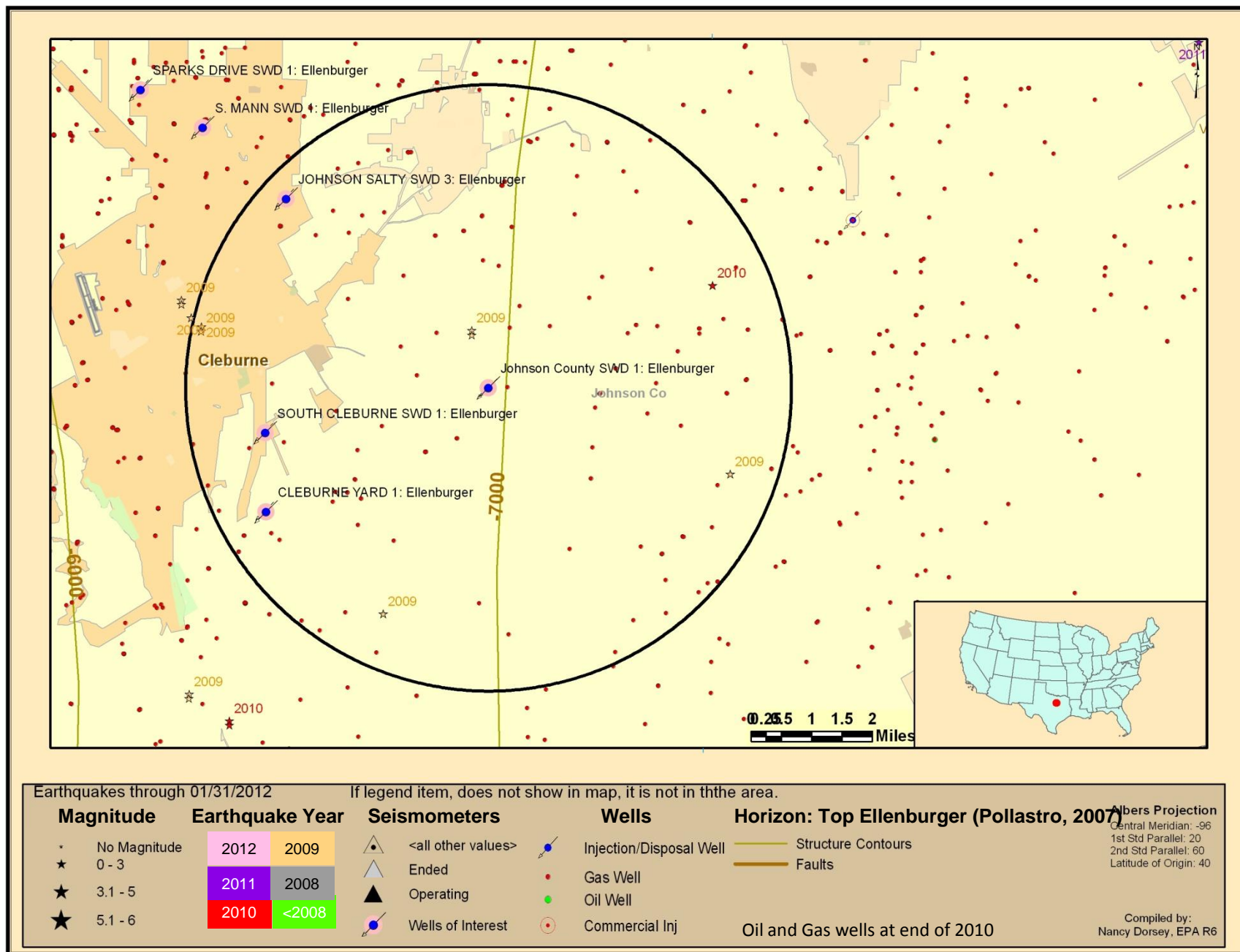
# FIGURE D-20: CLEBURNE AREA SEISMICITY AND INJECTION TIMELINE



# FIGURE D-21: CLEBURNE AREA SEISMICITY EXPANDED VIEW 1

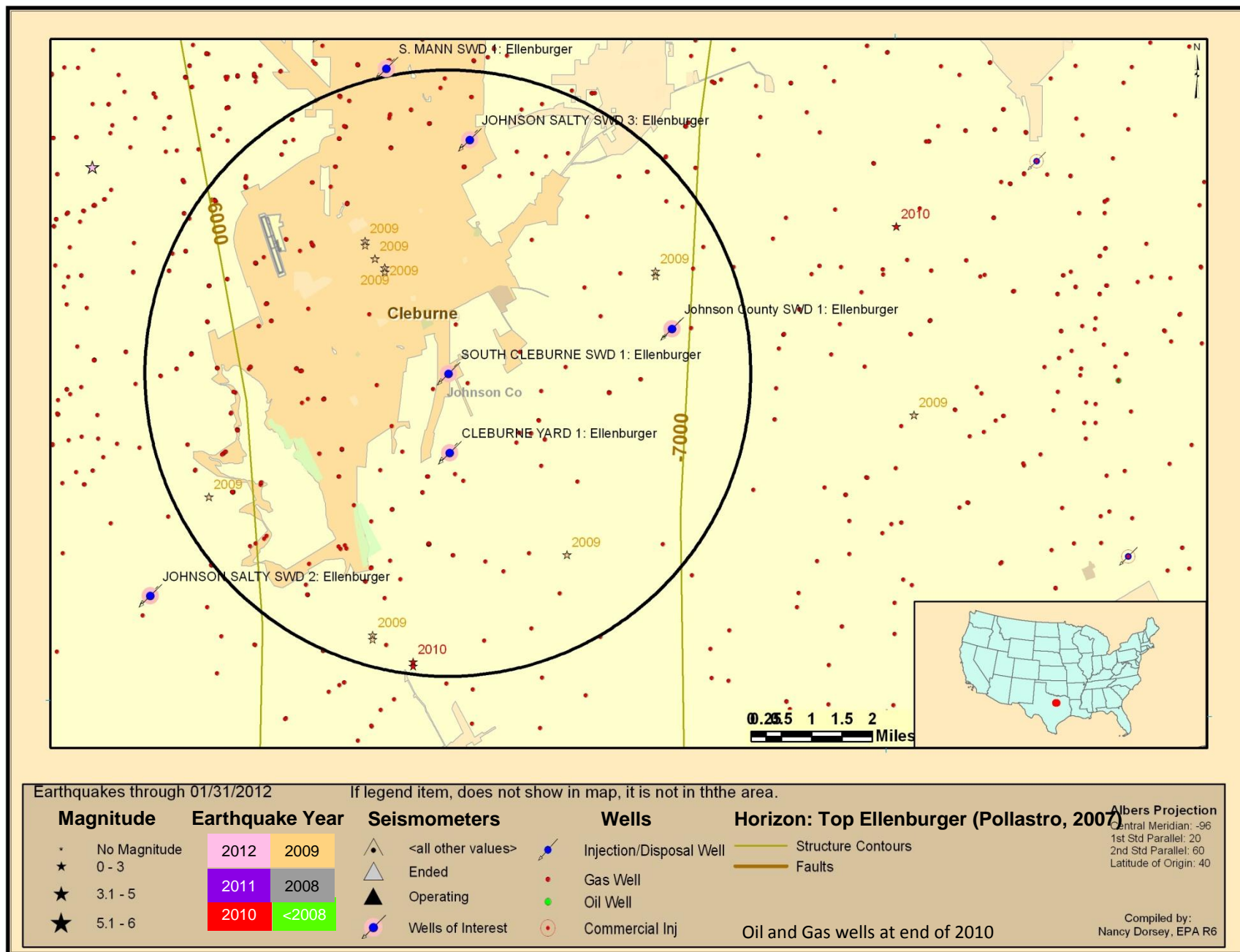


# FIGURE D-22: CLEBURNE AREA SEISMICITY EXPANDED VIEW 2

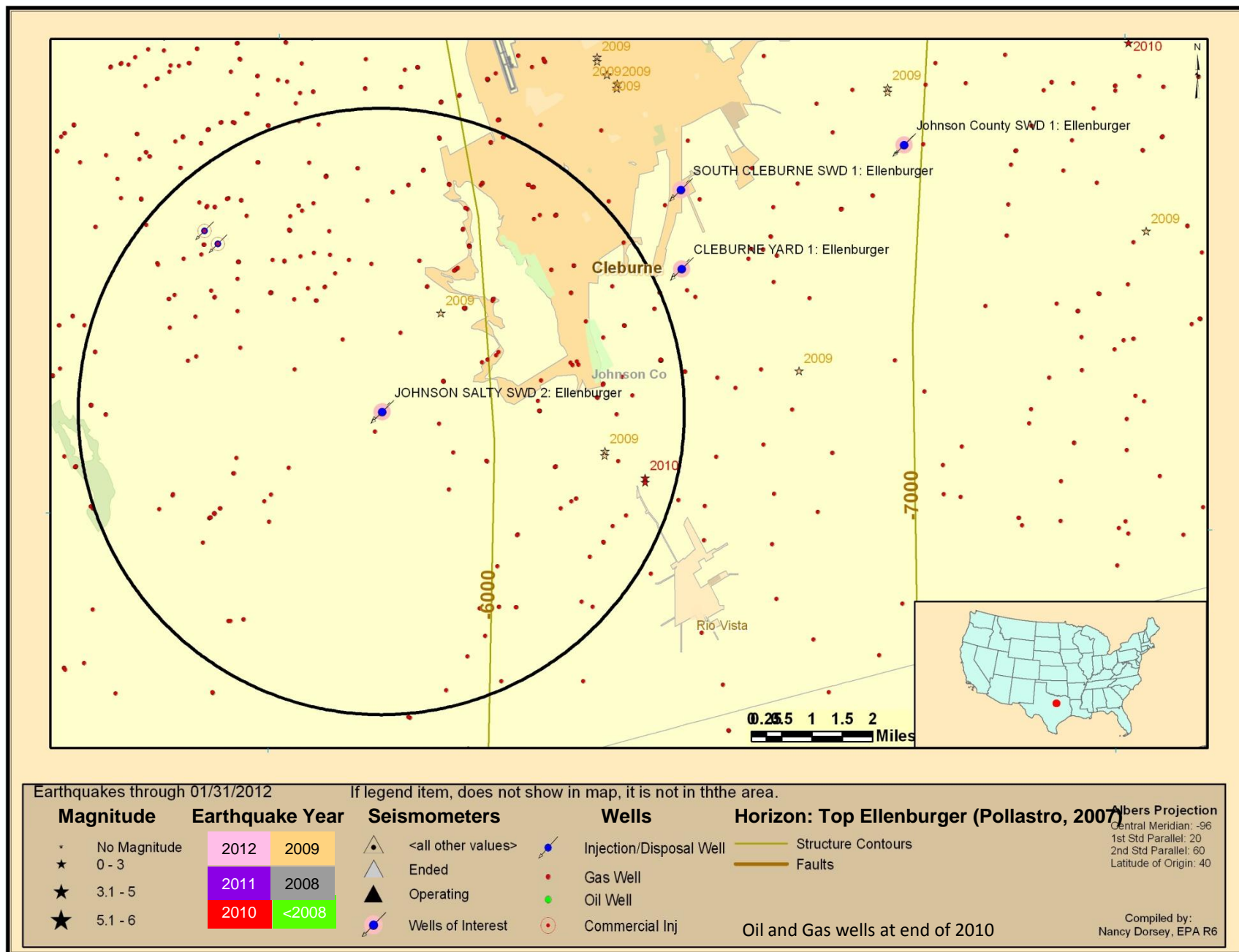




# FIGURE D-23: CLEBURNE AREA SEISMICITY EXPANDED VIEW 3



# FIGURE D-24: CLEBURNE AREA SEISMICITY EXPANDED VIEW 4





# FIGURE D-25: SPARKS DRIVE SWD 1 WELL SCHEMATIC

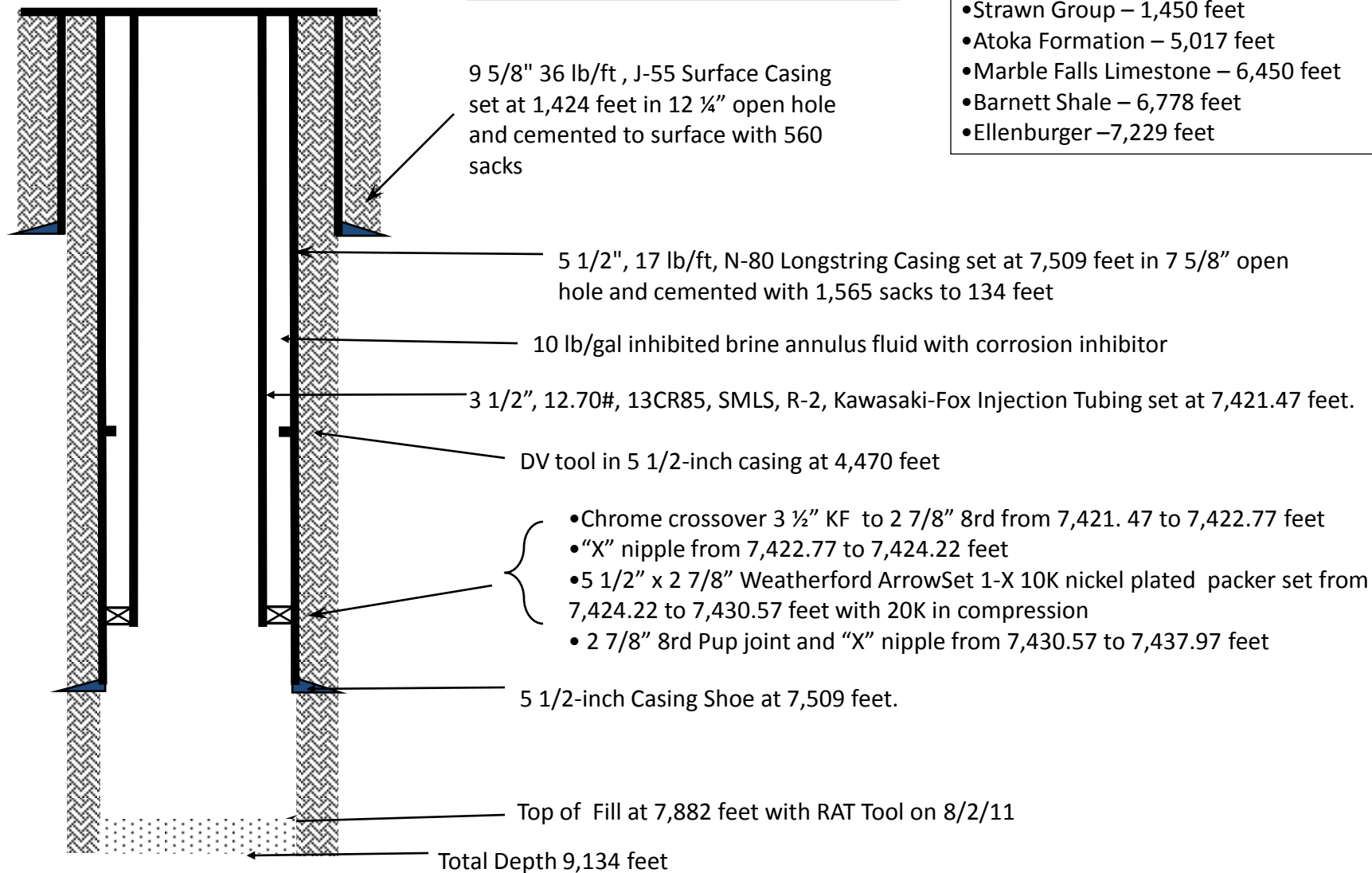
## Sparks Drive SWD/WDW-401

### Permitted Intervals

- Injection Zone – 7,454 to 9,134 feet
- Injection Interval – 7,509 to 9,134 feet

### Formation tops

- Base of USDW – 1,073 feet
- Canyon Group – 1,229 feet
- Strawn Group – 1,450 feet
- Atoka Formation – 5,017 feet
- Marble Falls Limestone – 6,450 feet
- Barnett Shale – 6,778 feet
- Ellenburger – 7,229 feet



NOTE: All Depths Relative to 5 1/2" Casing Shoe depth of 7,509 feet.

Static BHP 3,973.69 psia at 7,620 feet 8/2/11

FIGURE D-26: SPARKS DRIVE SWD 1 OPERATING DATA OVERVIEW PLOT

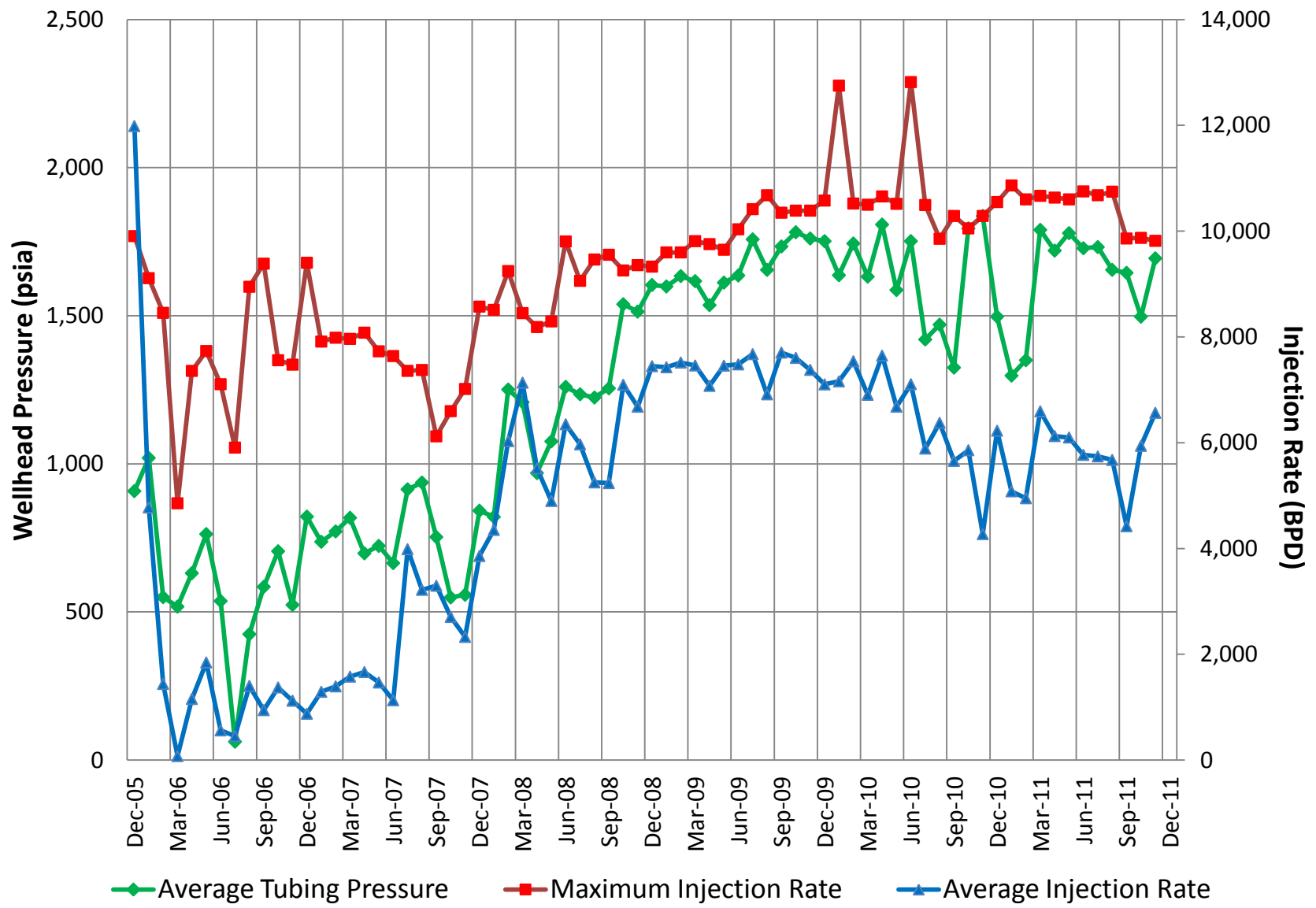


FIGURE D-27: S. MANN SWD 1 OPERATING DATA OVERVIEW PLOT

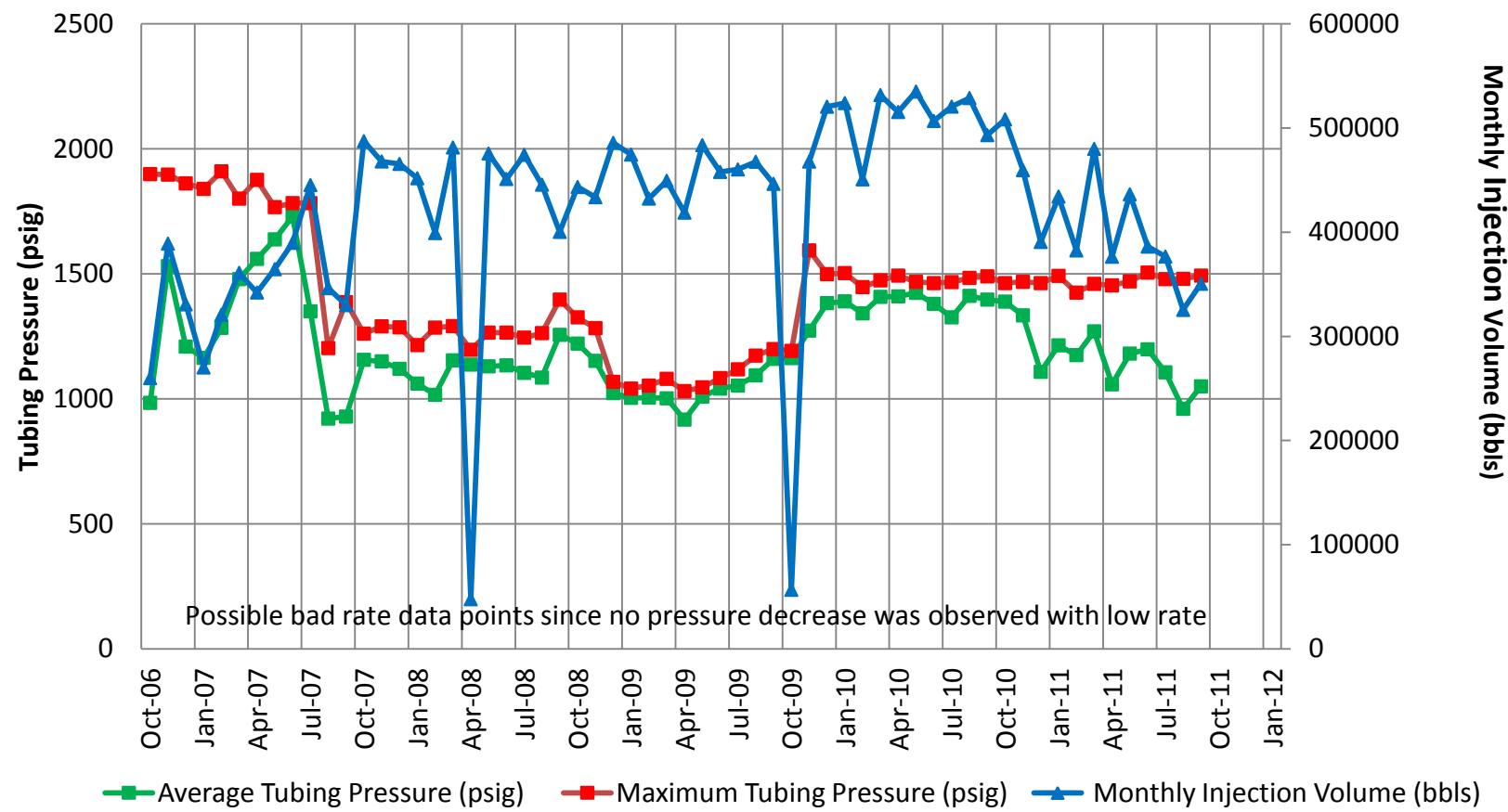


FIGURE D-28: S. CLEBURNE SWD 1 OPERATING DATA OVERVIEW PLOT

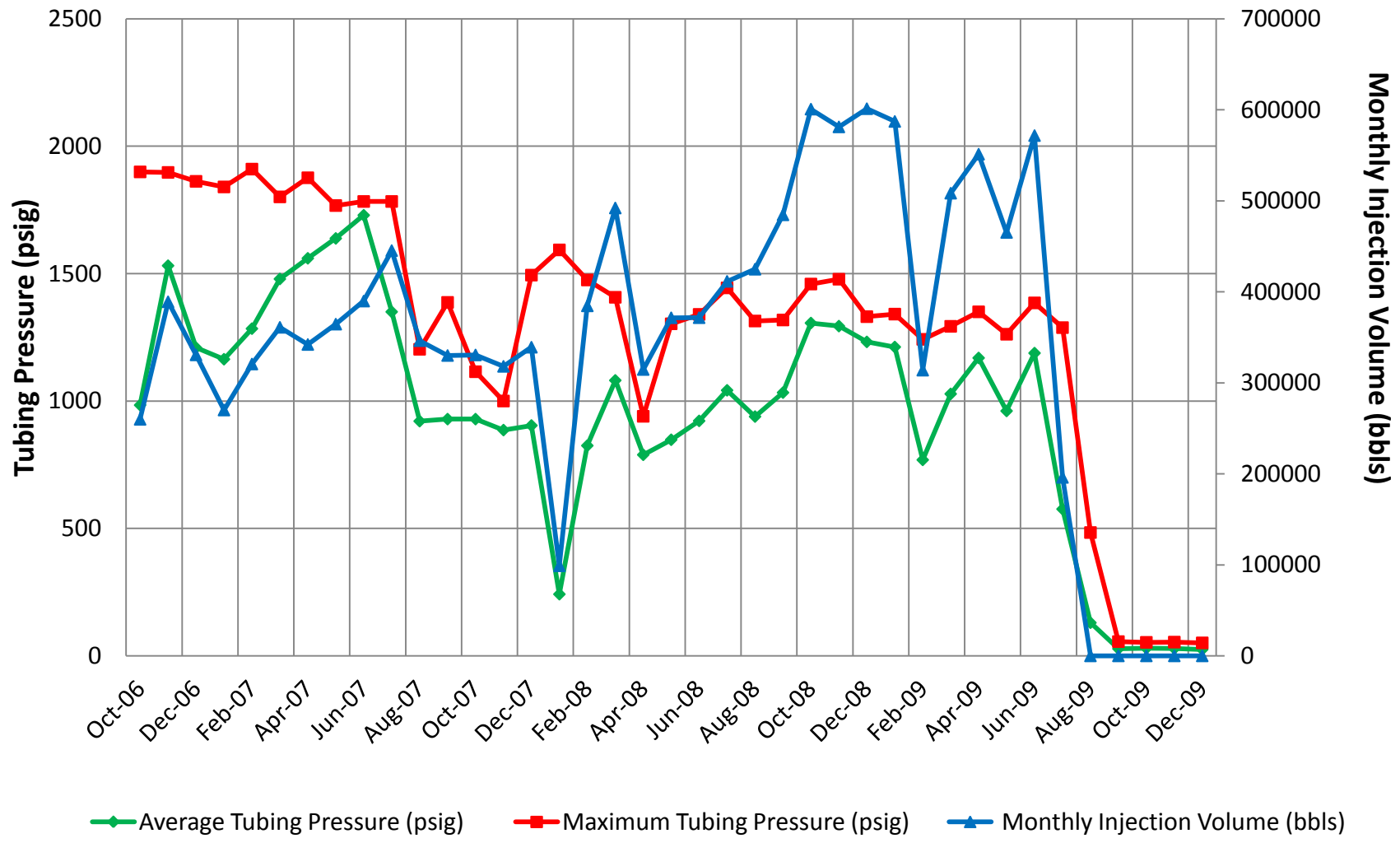


FIGURE D-29: SALTY SWD II OPERATING DATA OVERVIEW PLOT

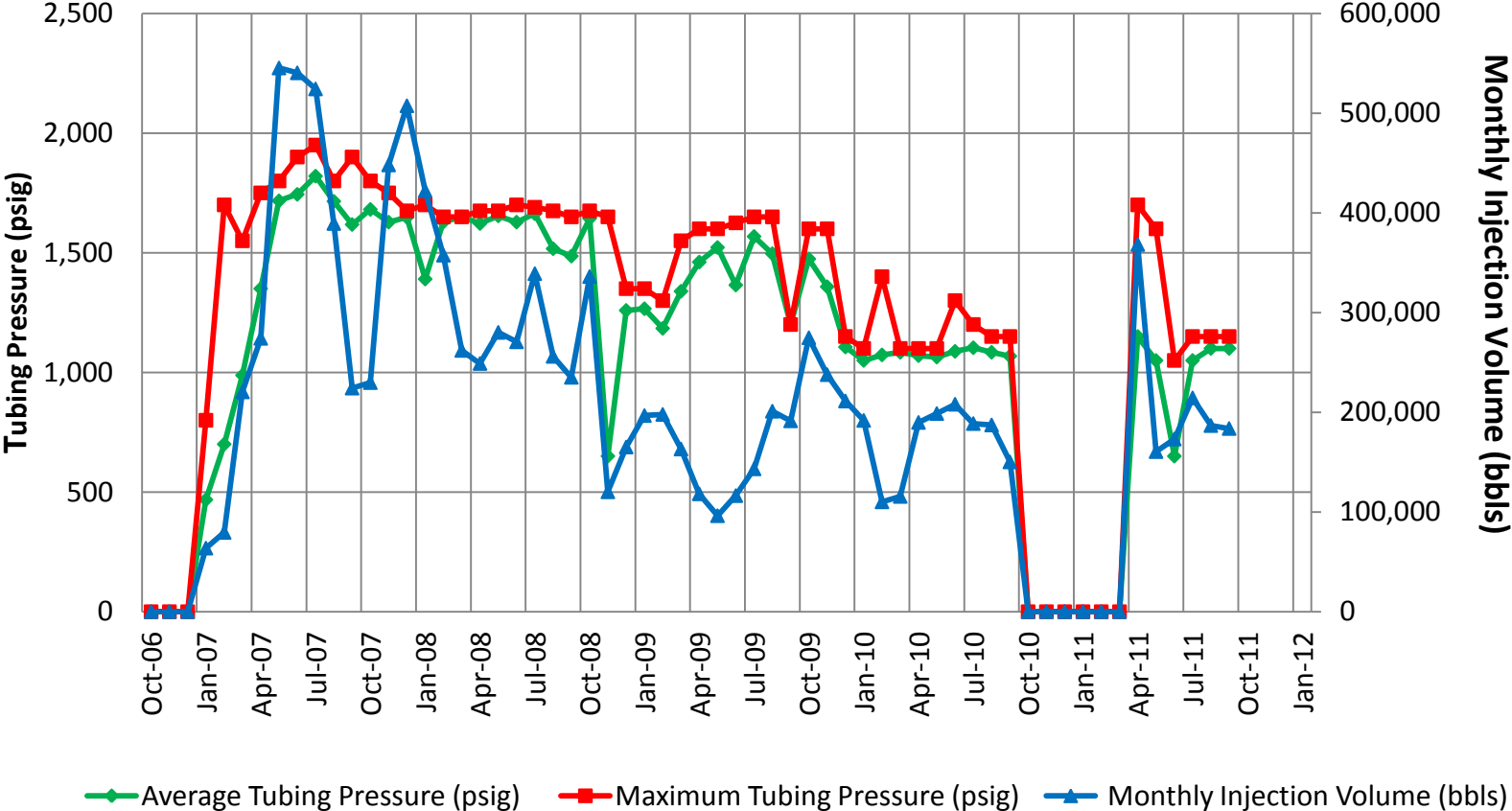
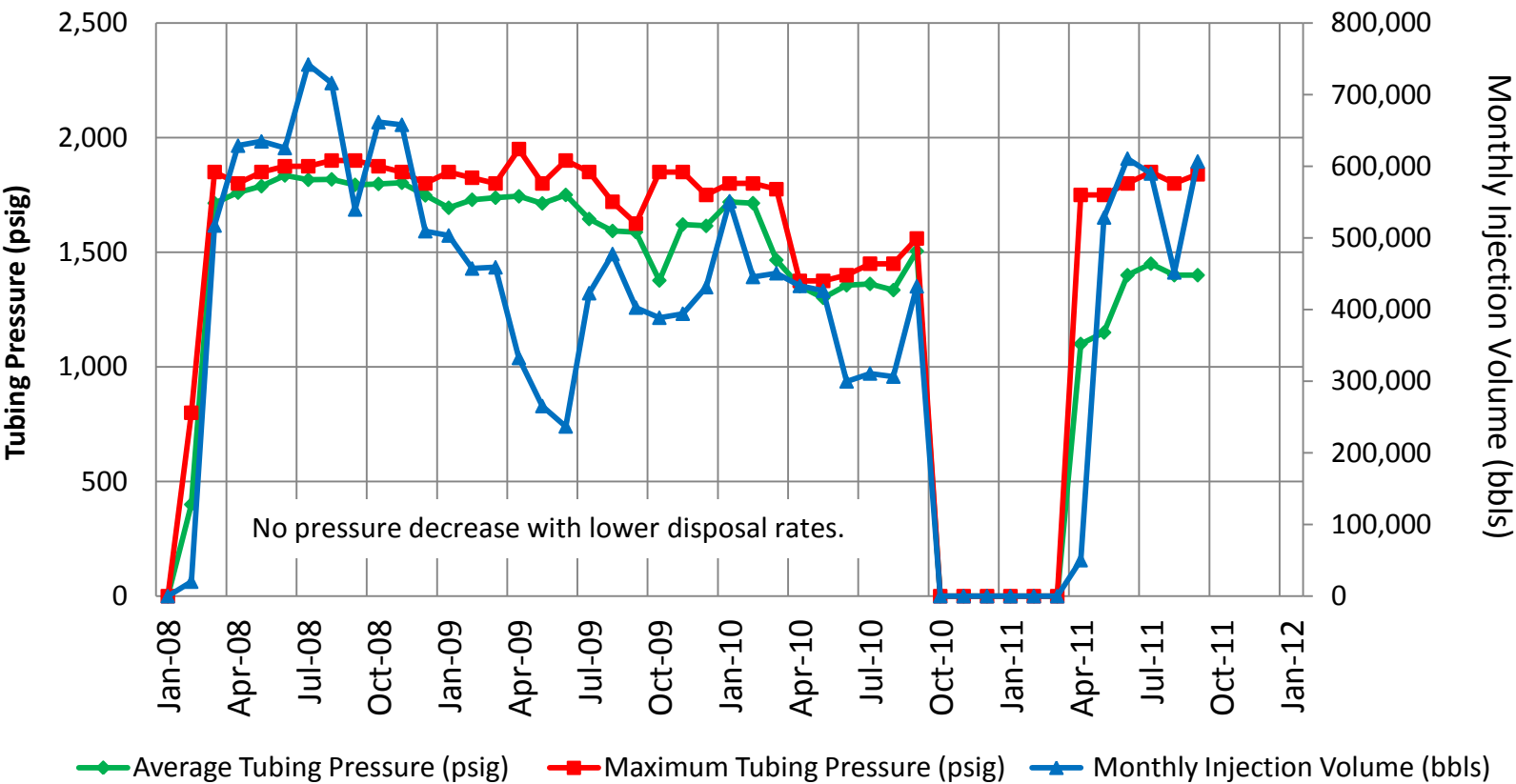
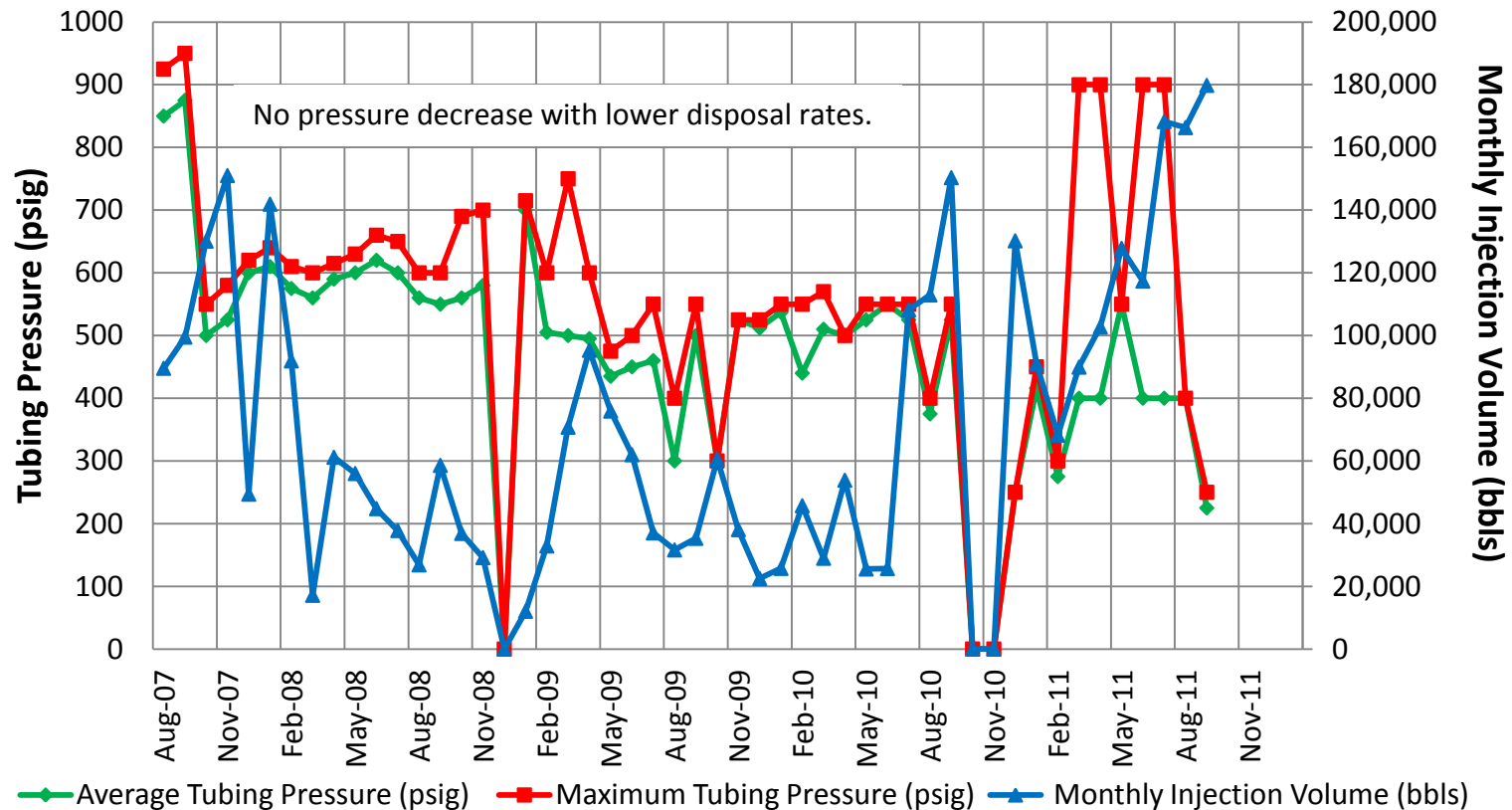


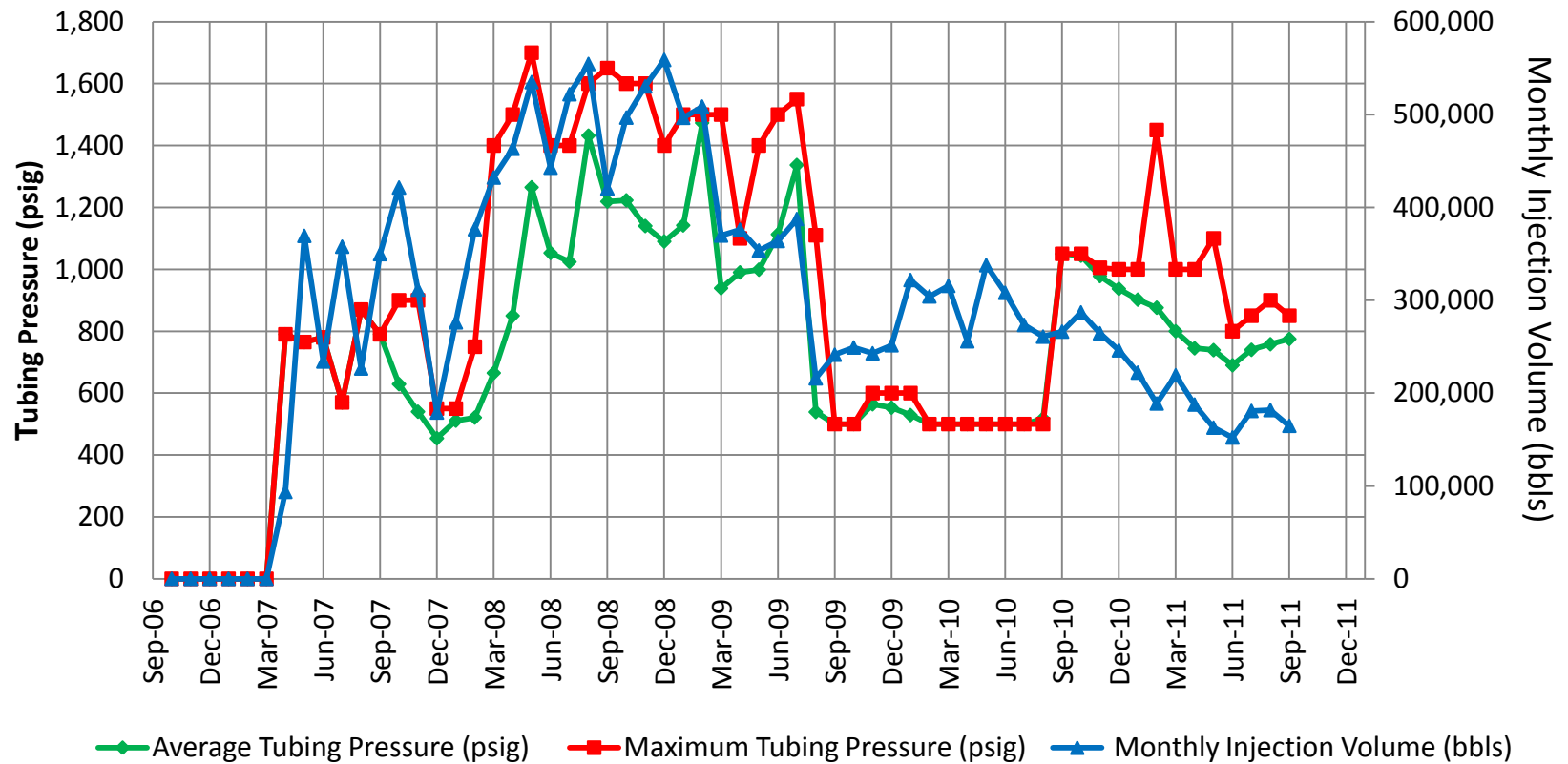
FIGURE D-30: JOHNSON SALTY SWD III OPERATING DATA OVERVIEW PLOT



**FIGURE D-31: CLEBURNE YARD SWD 1 OPERATING DATA OVERVIEW PLOT**



**FIGURE D-32: JOHNSON CO. SWD 1 OPERATING DATA OVERVIEW PLOT**





**FIGURE D-33: SPARKS DRIVE SWD 1 OPERATING PRESSURE GRADIENT PLOT**

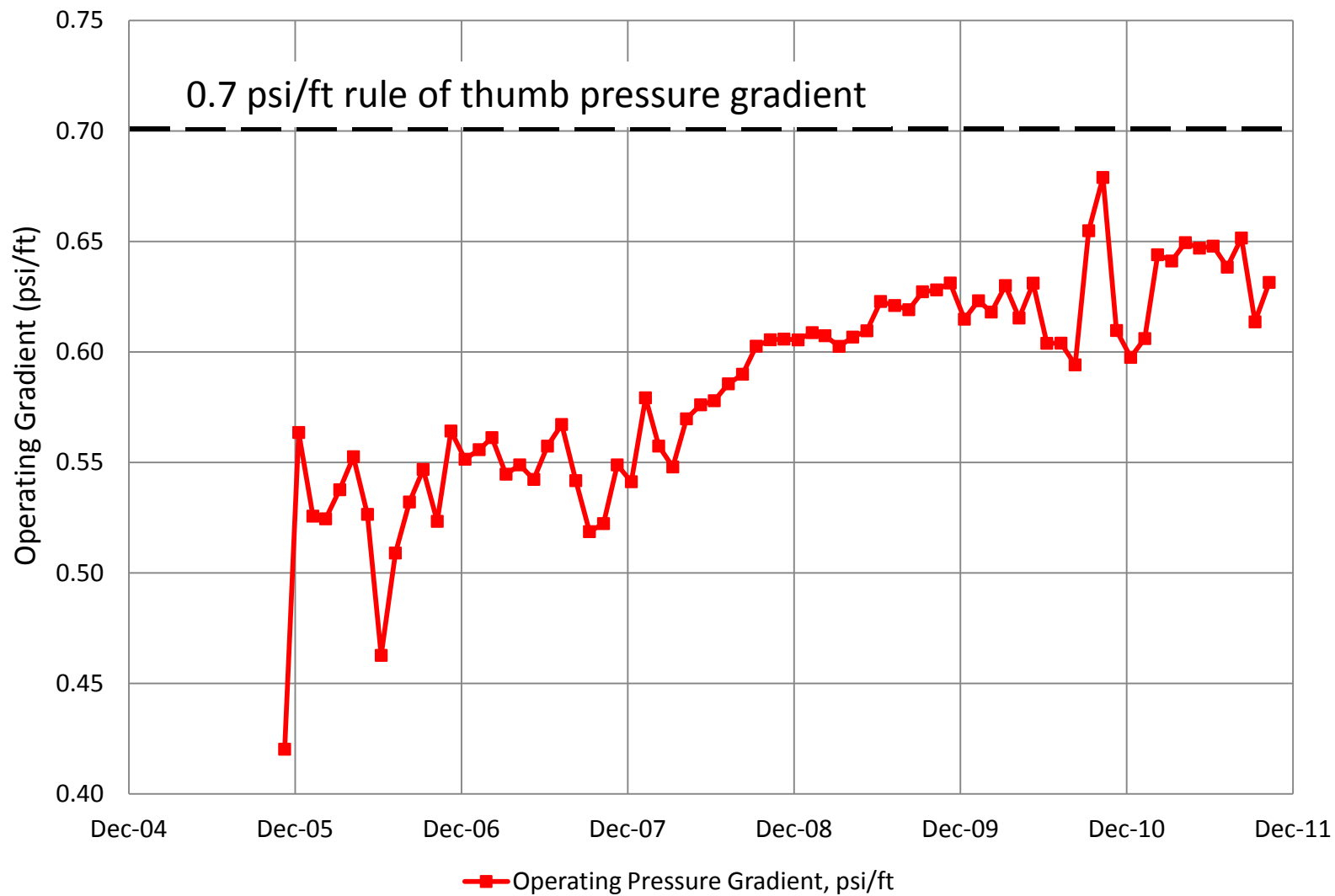


FIGURE D-34: S. MANN SWD 1 OPERATING PRESSURE GRADIENT PLOT

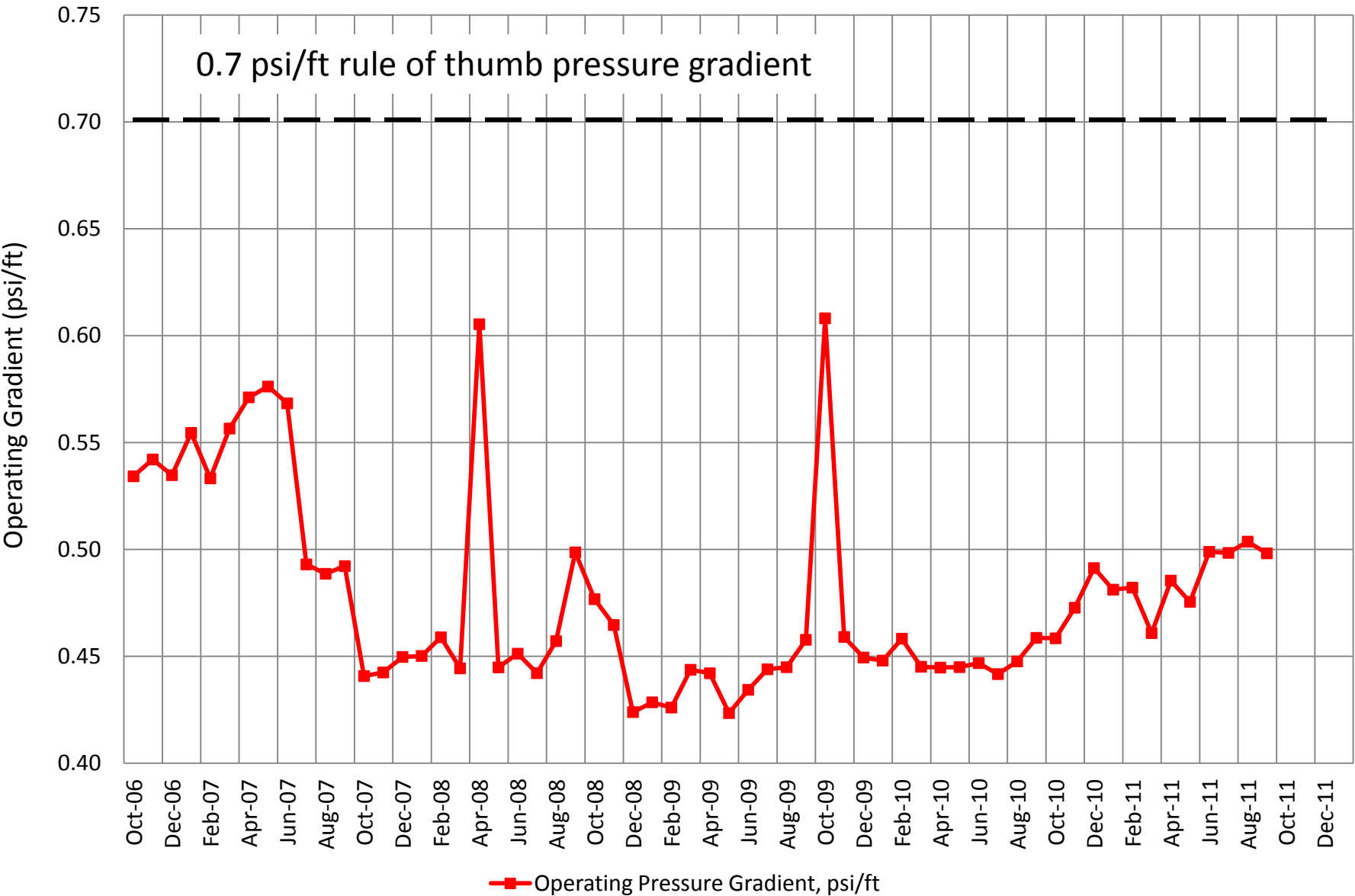


FIGURE D-35: S. CLEBURNE SWD 1 OPERATING PRESSURE GRADIENT PLOT

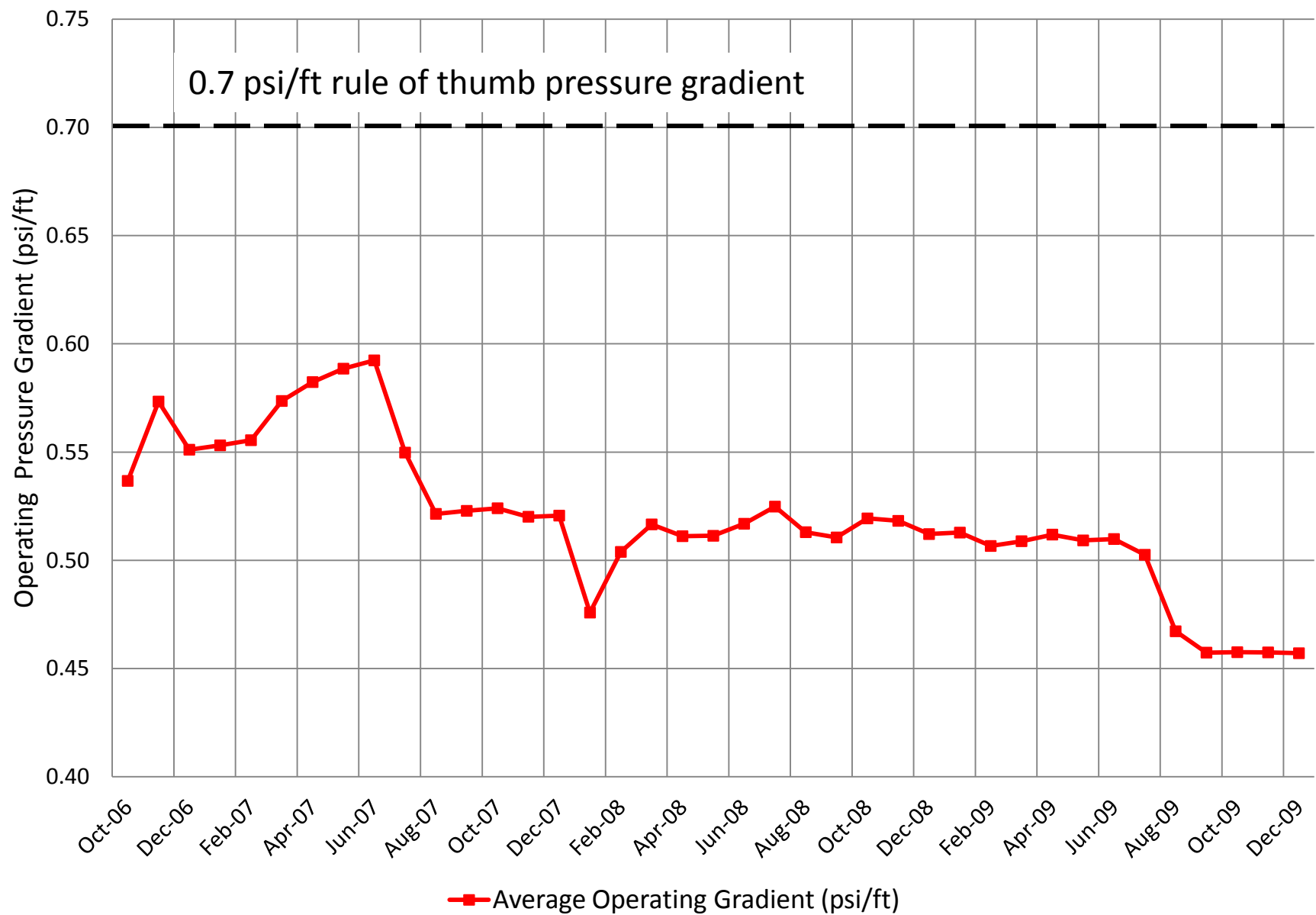
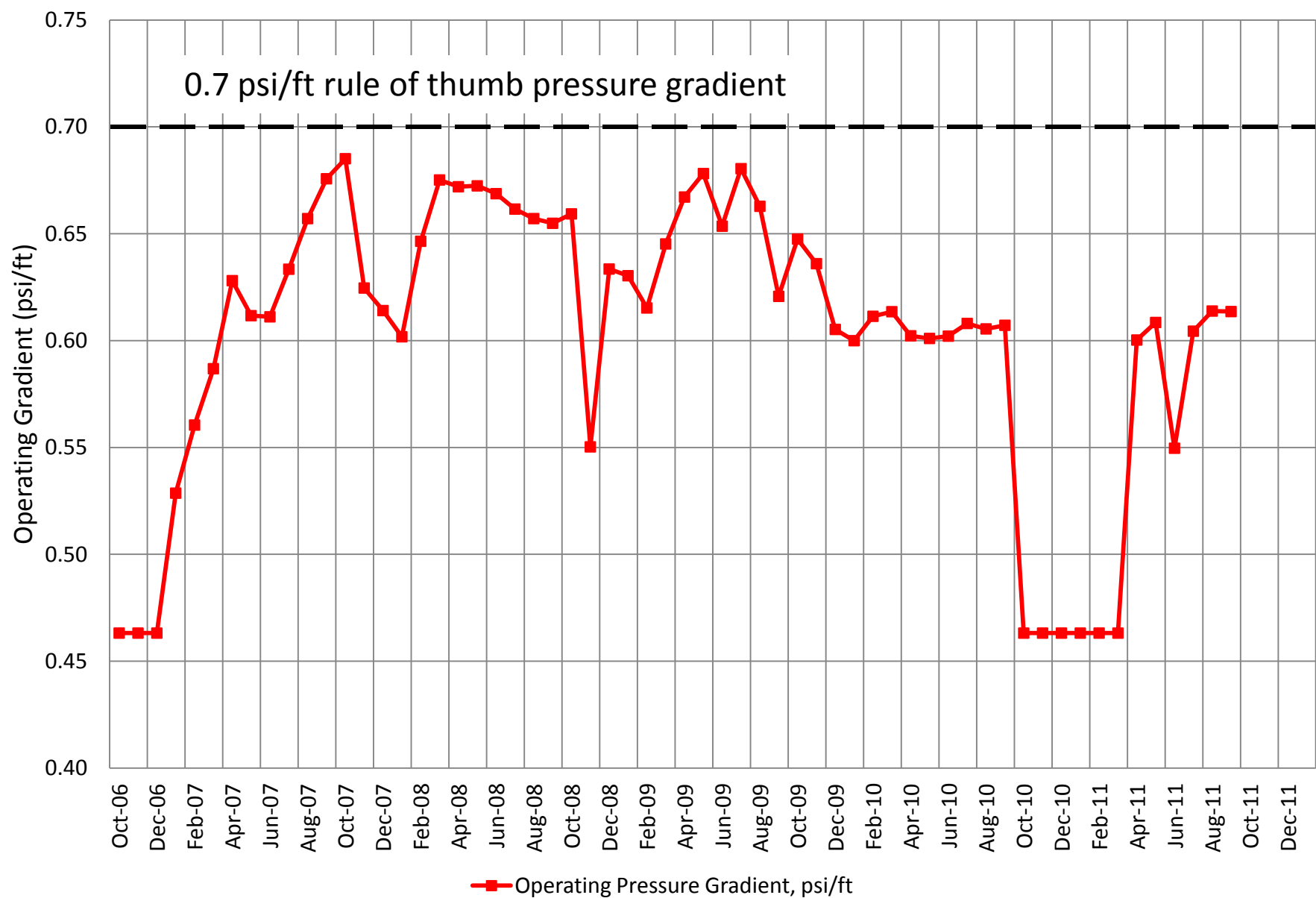
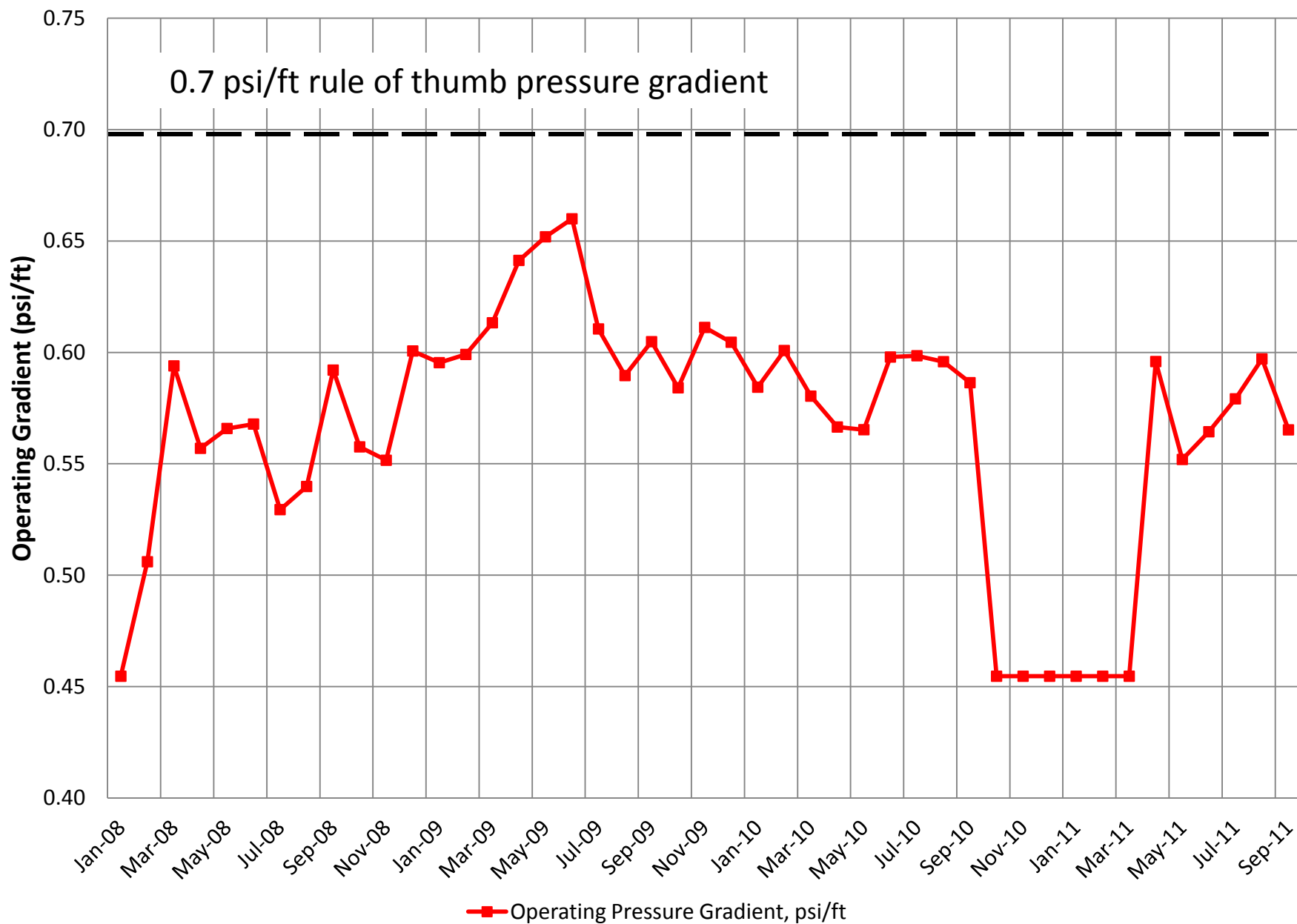
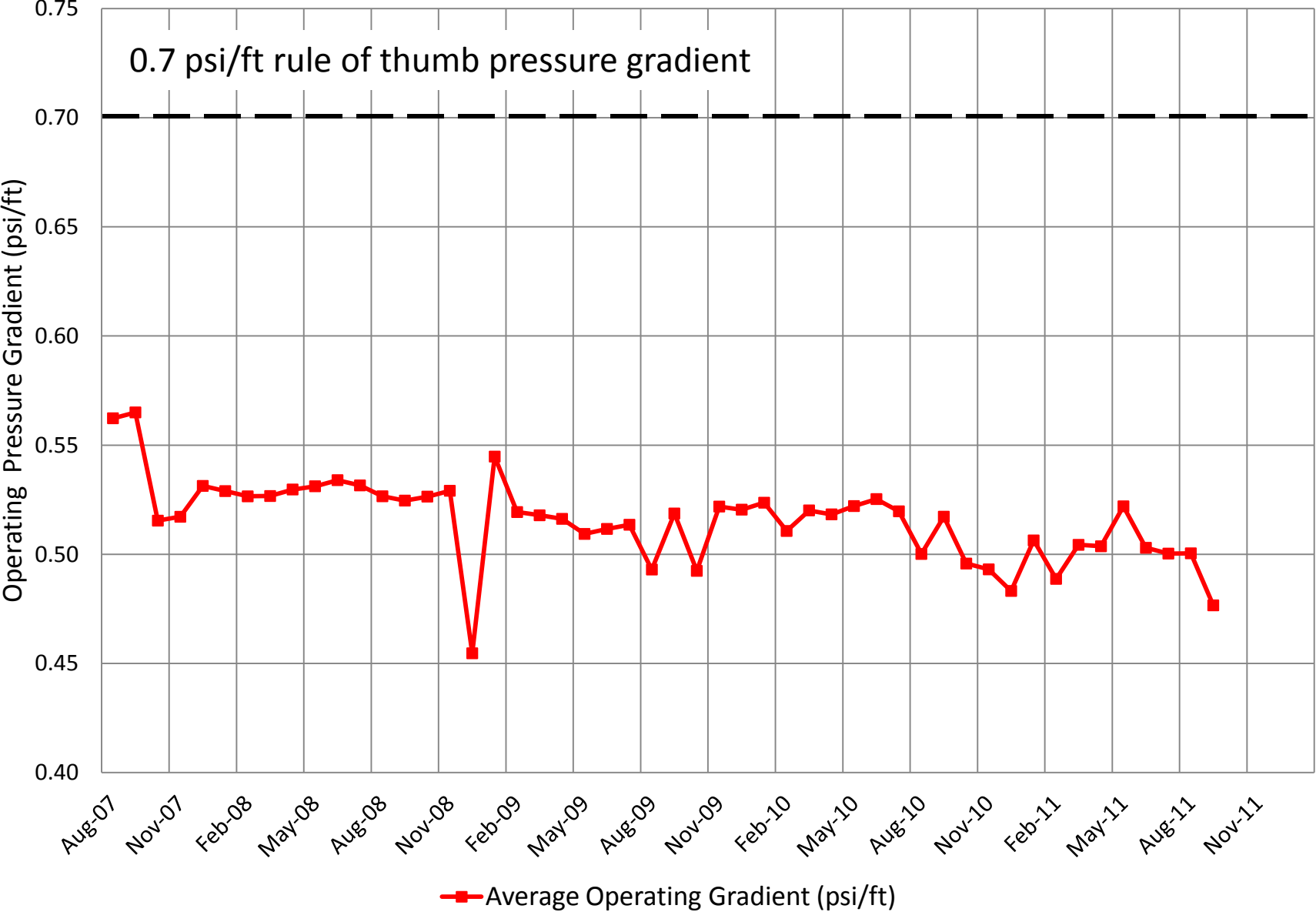


FIGURE D-36: SALTY SWD II OPERATING PRESSURE GRADIENT PLOT

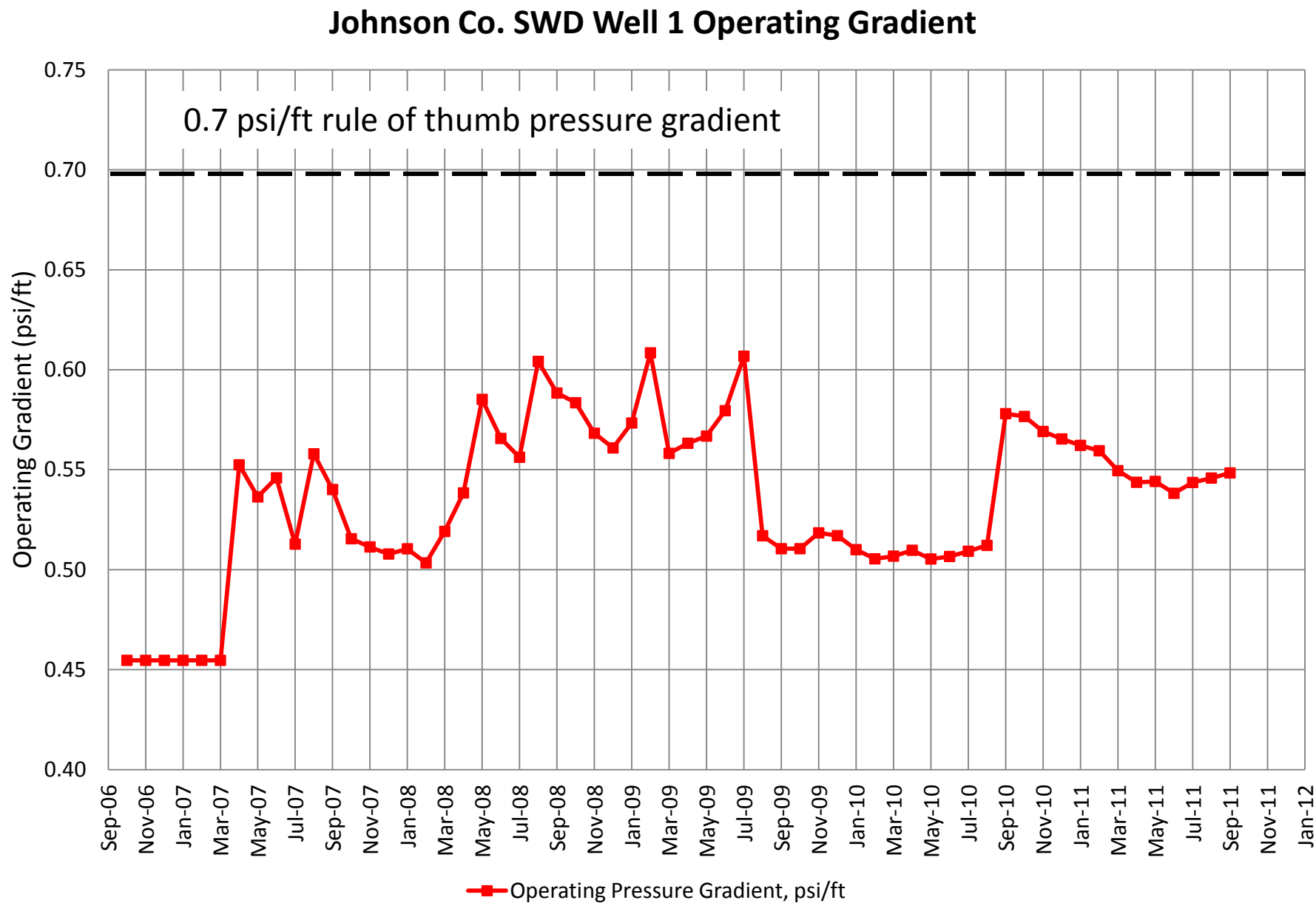




**FIGURE D-38: CLEBURNE YARD SWD 1 OPERATING PRESSURE GRADIENT PLOT**



**FIGURE D-39: JOHNSON CO. SWD 1 OPERATING PRESSURE GRADIENT PLOT**



**FIGURE D-40: SPARKS DRIVE SWD 1 HALL INTEGRAL AND DERIVATIVE PLOT**

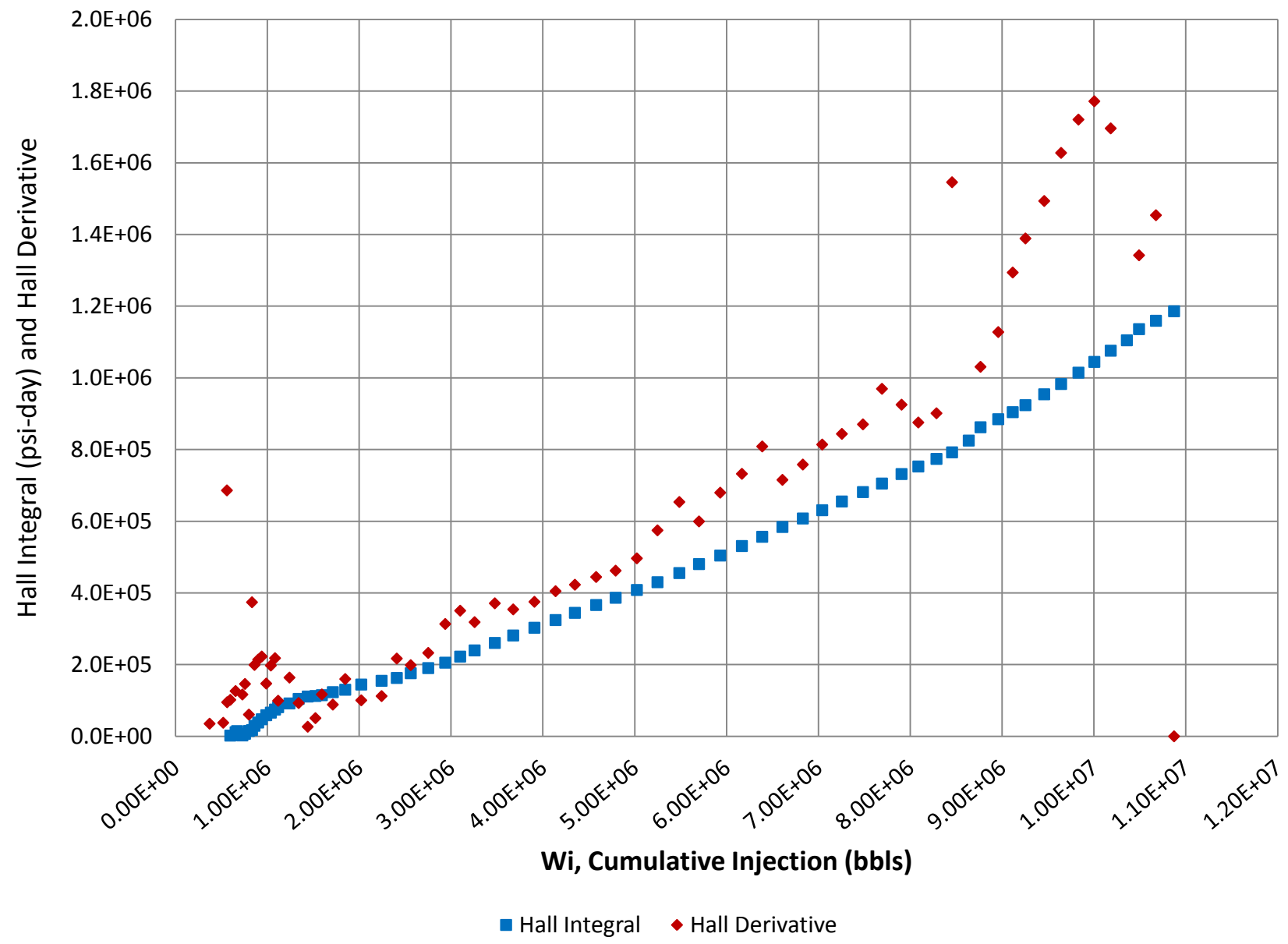
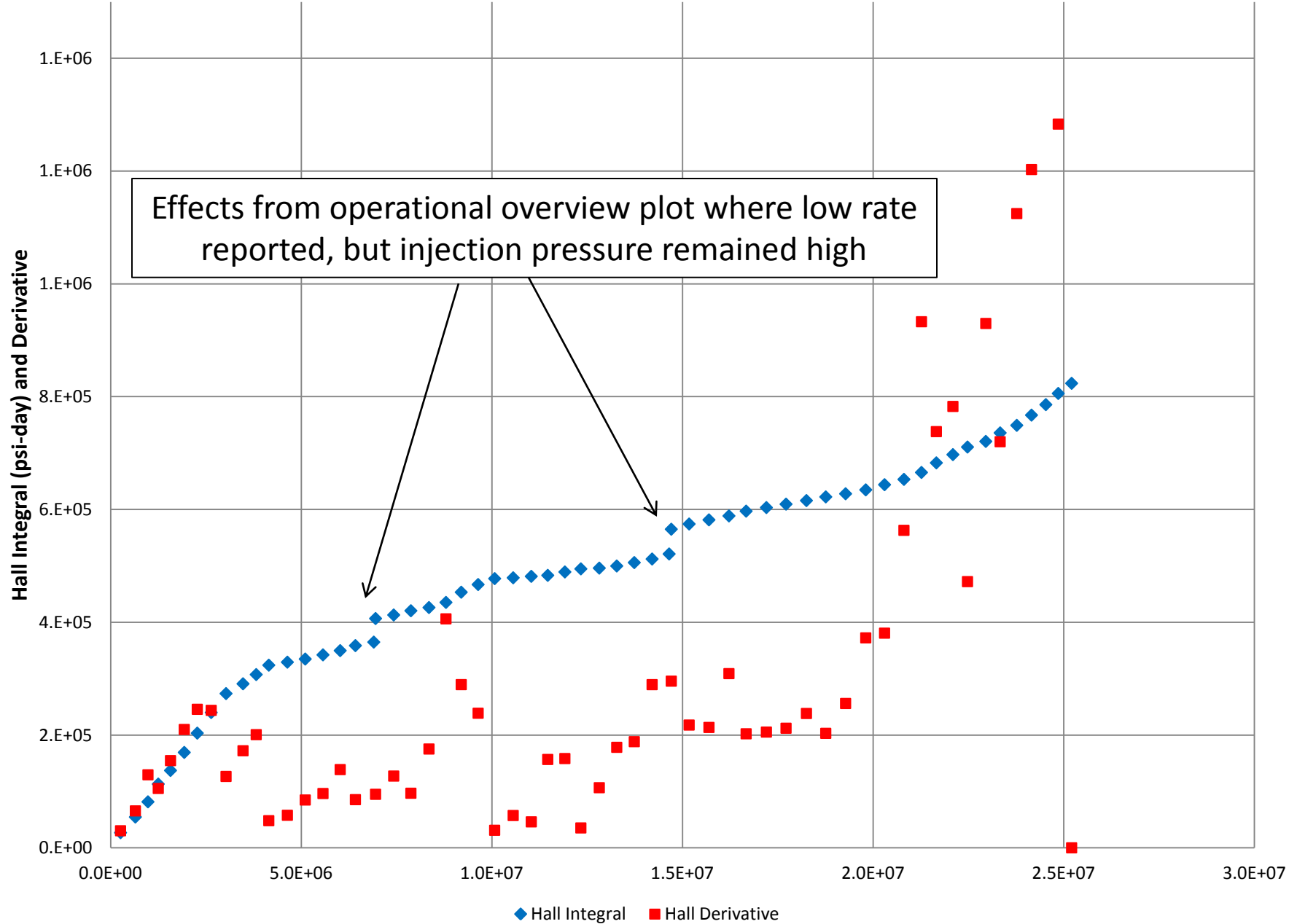
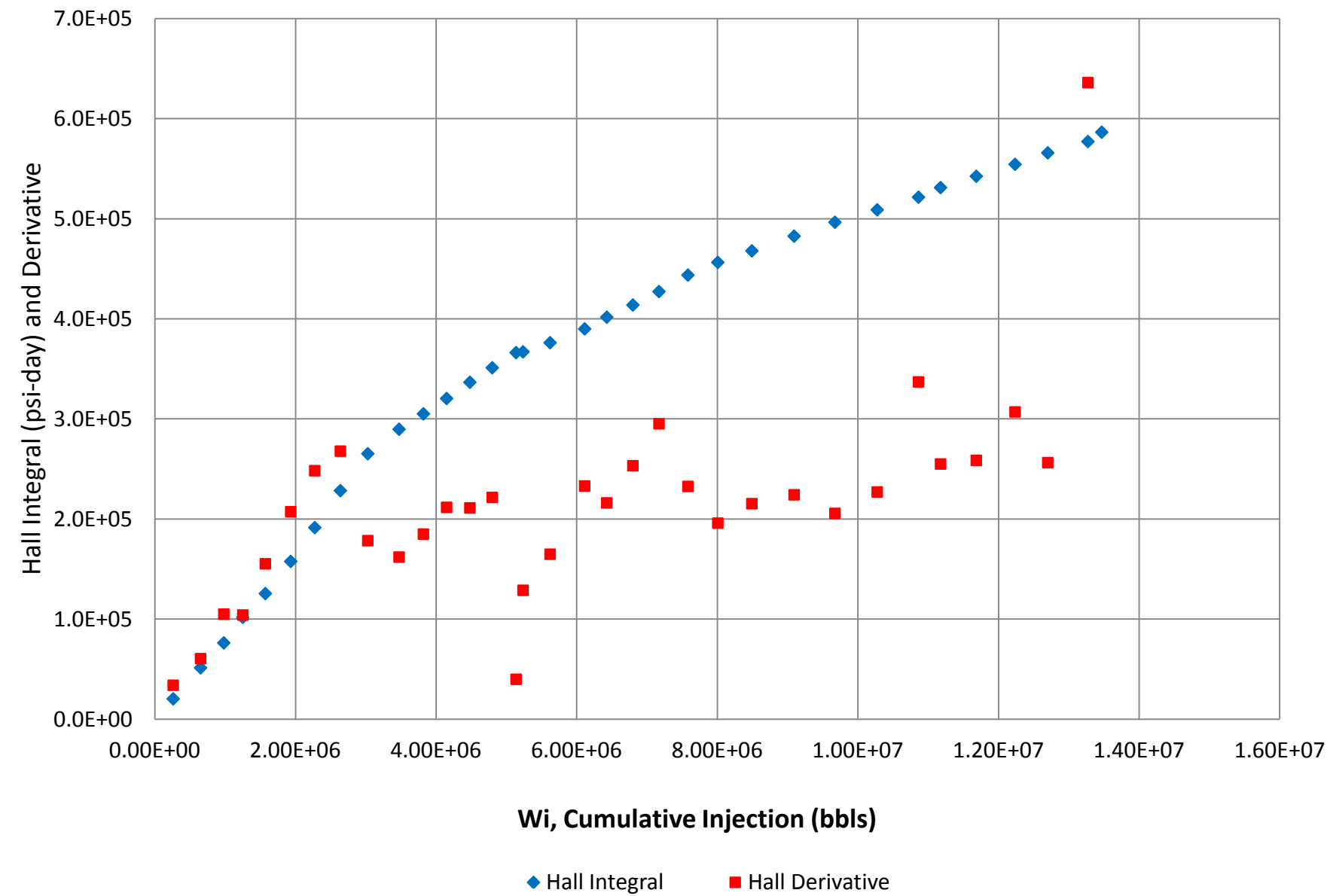




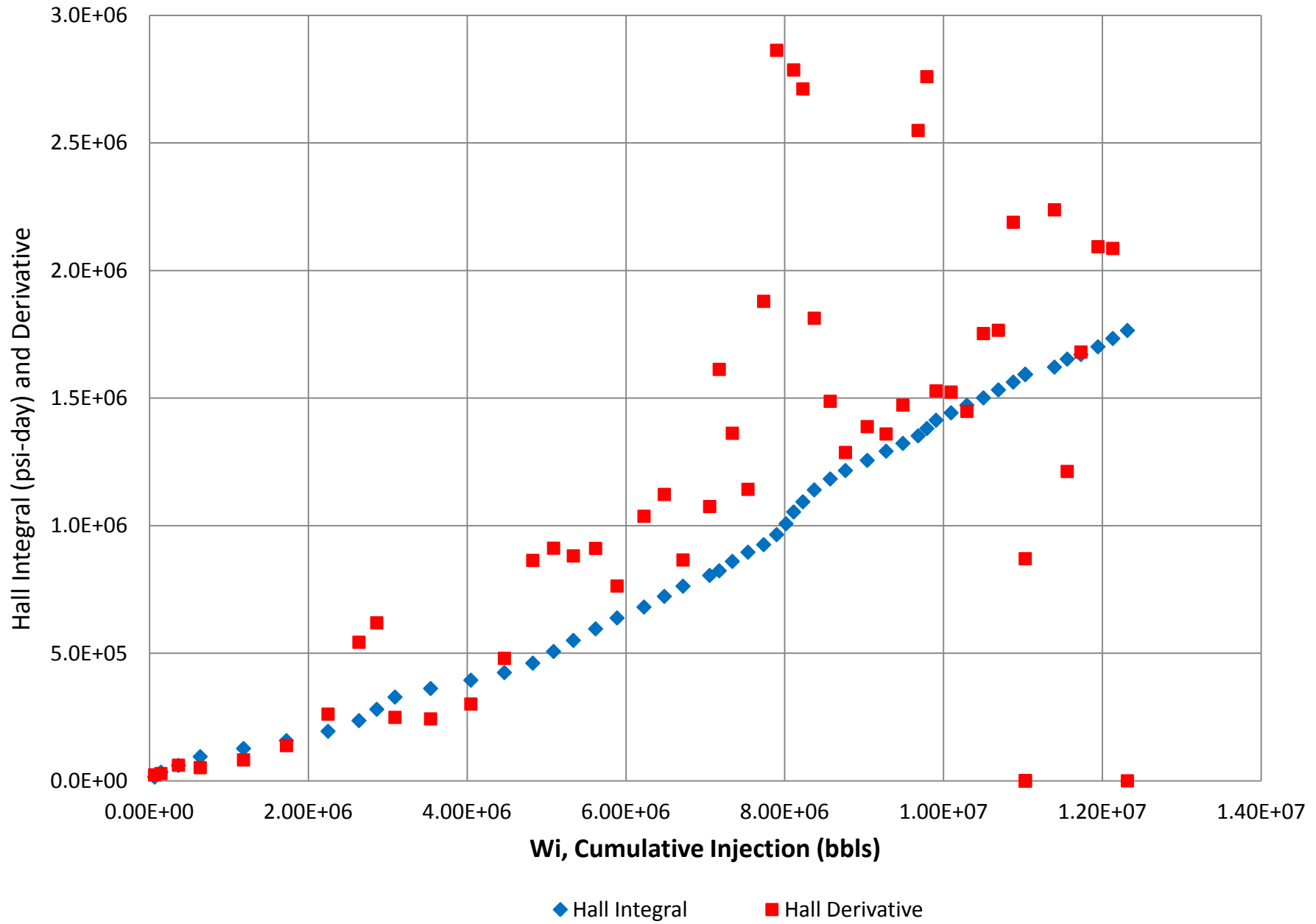
FIGURE D-41: S. MANN SWD 1 HALL INTEGRAL AND DERIVATIVE PLOT



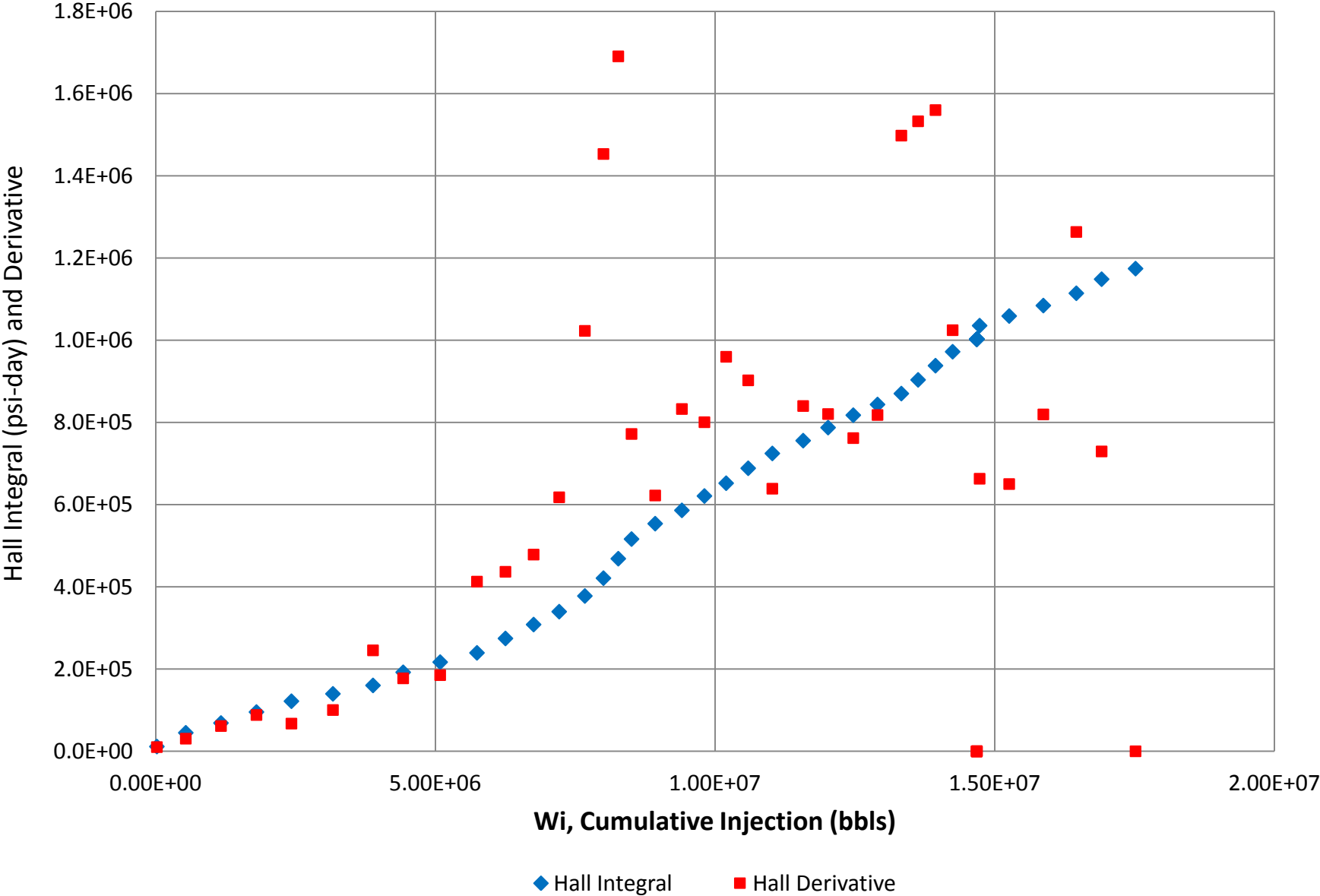
**FIGURE D-42: S. CLEBURNE SWD 1 HALL INTEGRAL AND DERIVATIVE PLOT**



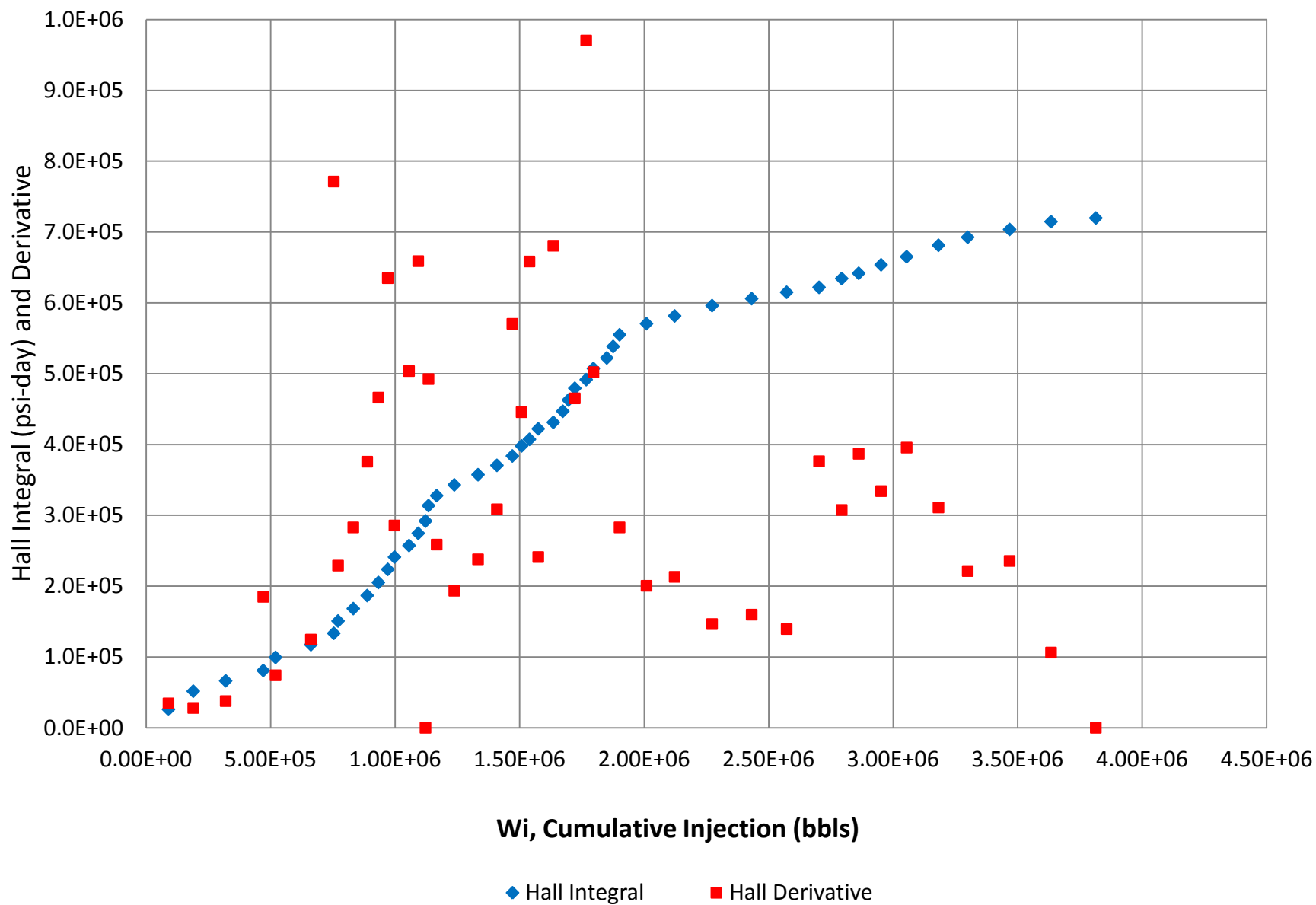
**FIGURE D-43: SALTY SWD II HALL INTEGRAL AND DERIVATIVE PLOT**



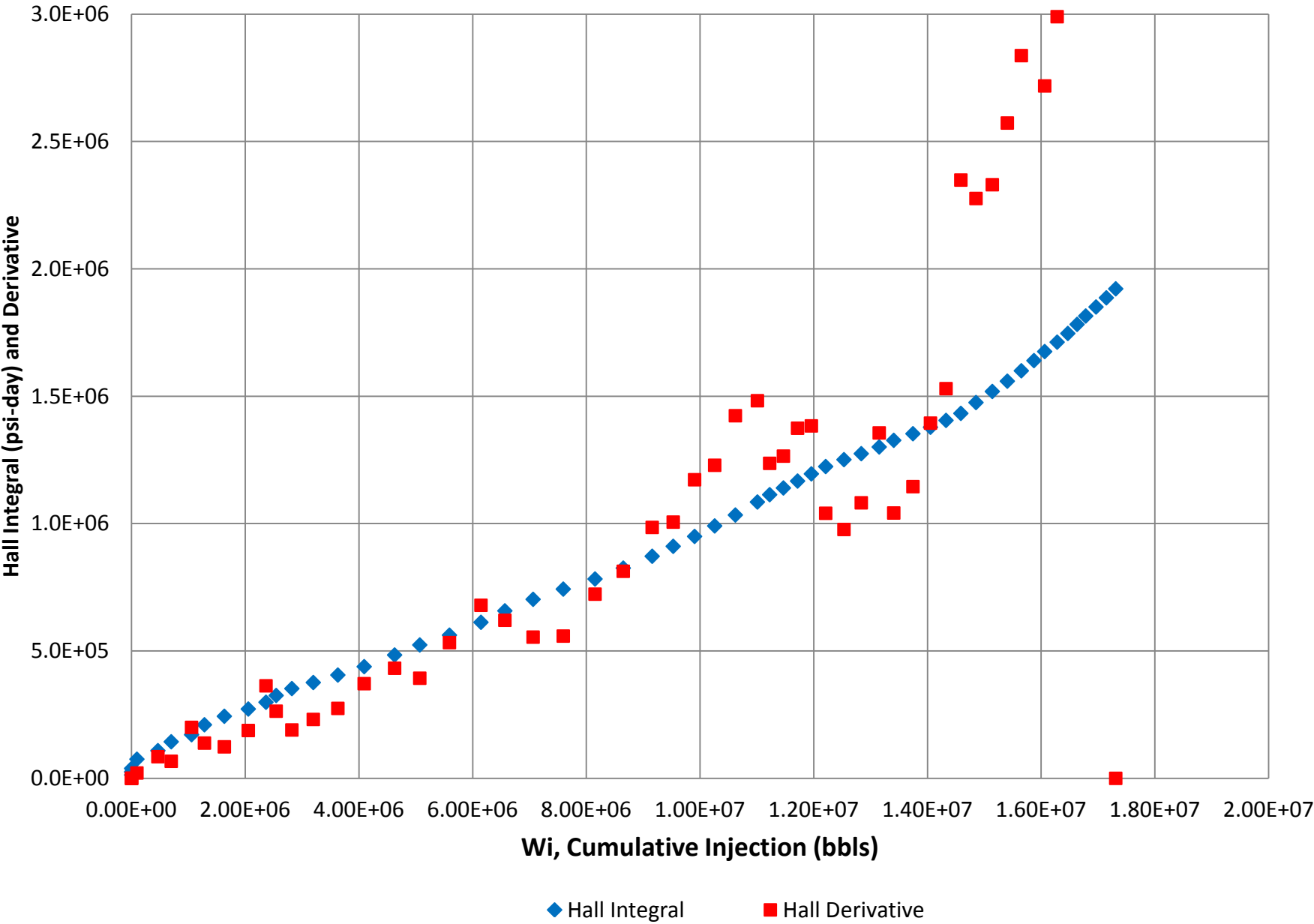
**FIGURE D-44: SALTY SWD III HALL INTEGRAL AND DERIVATIVE PLOT**



**FIGURE D-45: CLEBURNE YARD SWD 1 HALL INTEGRAL AND DERIVATIVE PLOT**



**FIGURE D-46: JOHNSON COUNTY SWD 1 HALL INTEGRAL AND DERIVATIVE PLOT**



**FIGURE D-47: SPARKS DRIVE SWD 1 SILIN SLOPE PLOT**

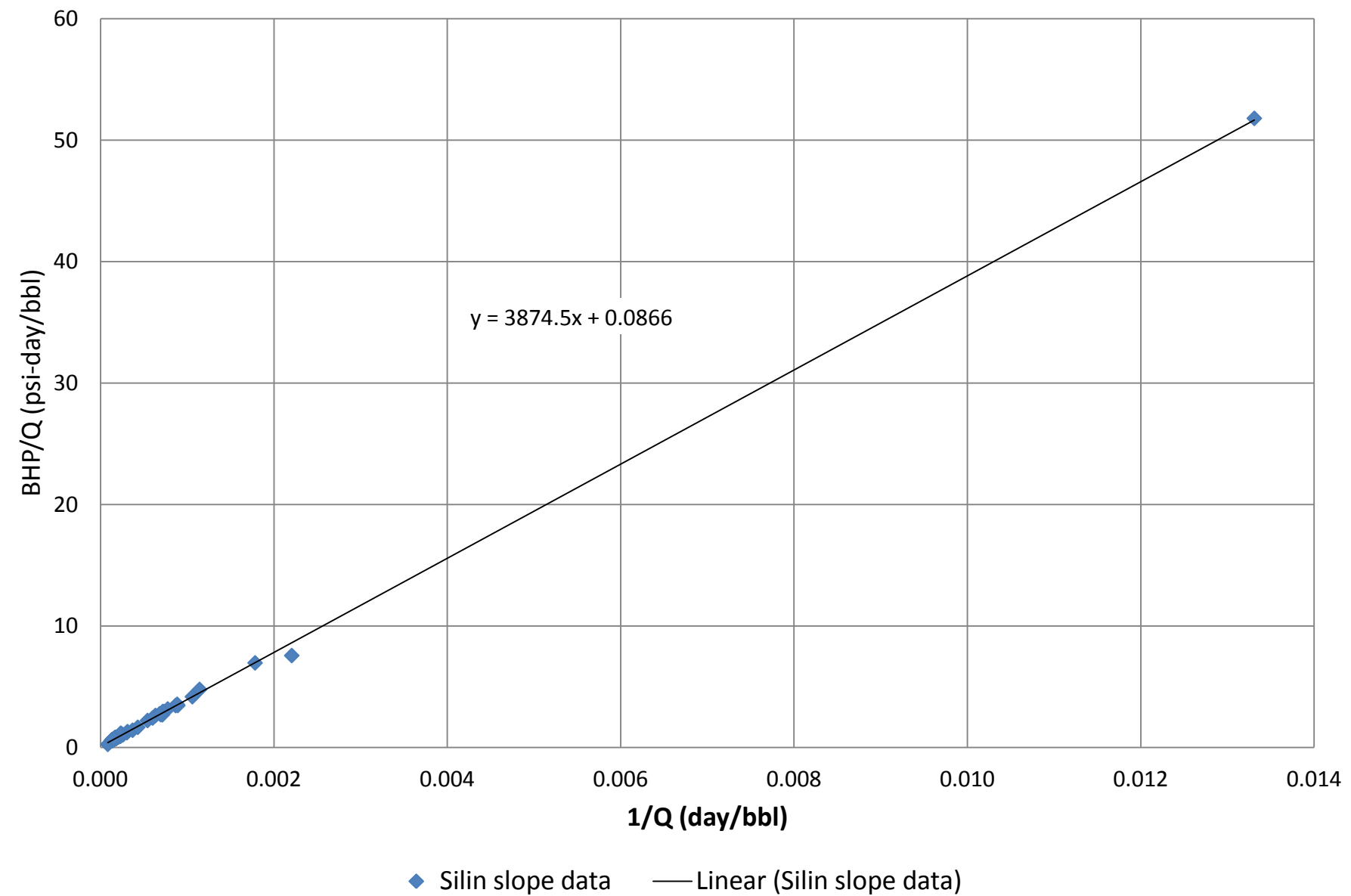
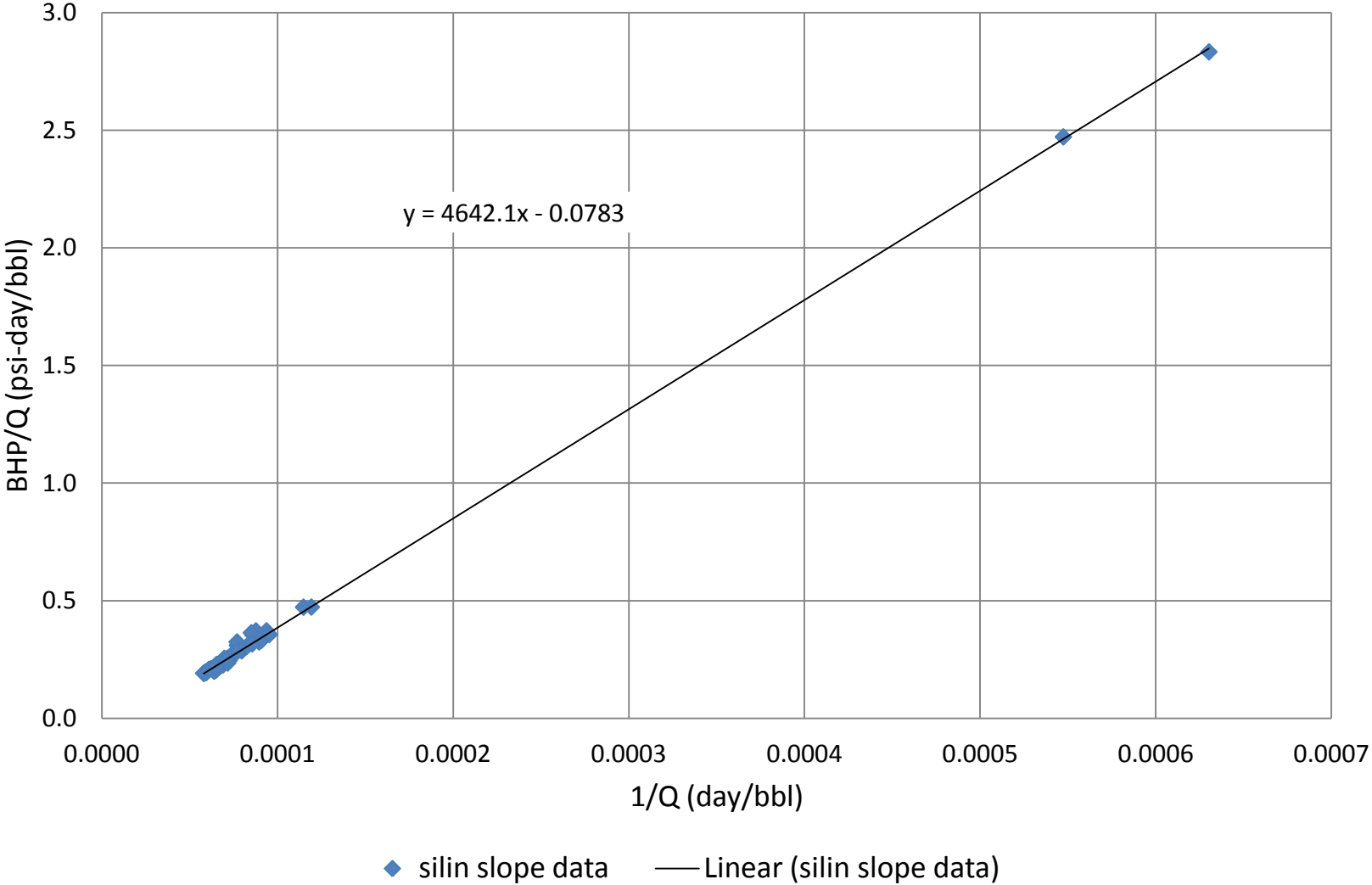


FIGURE D-48: S. MANN SWD 1 SILIN SLOPE PLOT





**FIGURE D-49: S. CLEBURNE SWD 1 SILIN SLOPE PLOT**

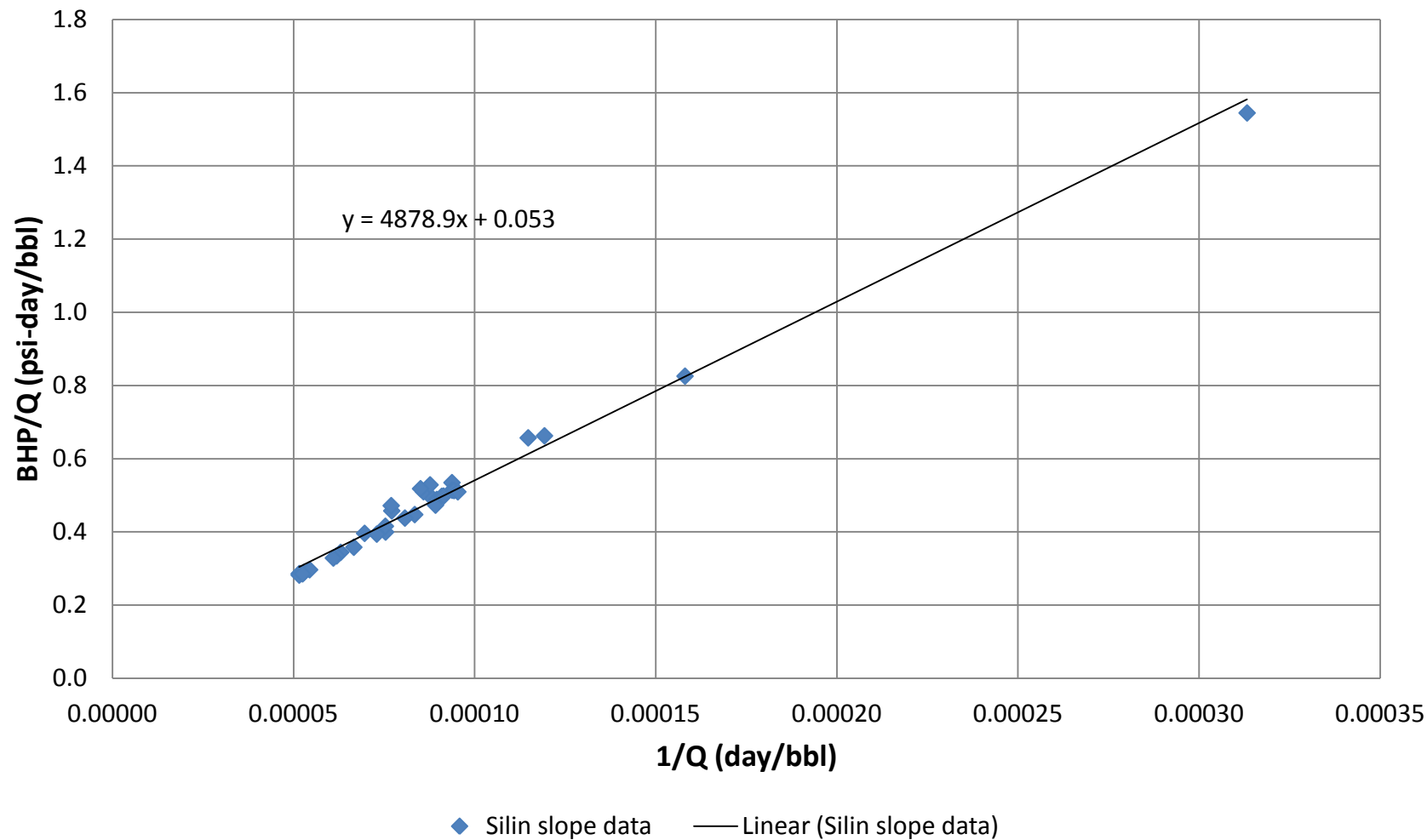


FIGURE D-50: SALTY SWD II SILIN SLOPE PLOT

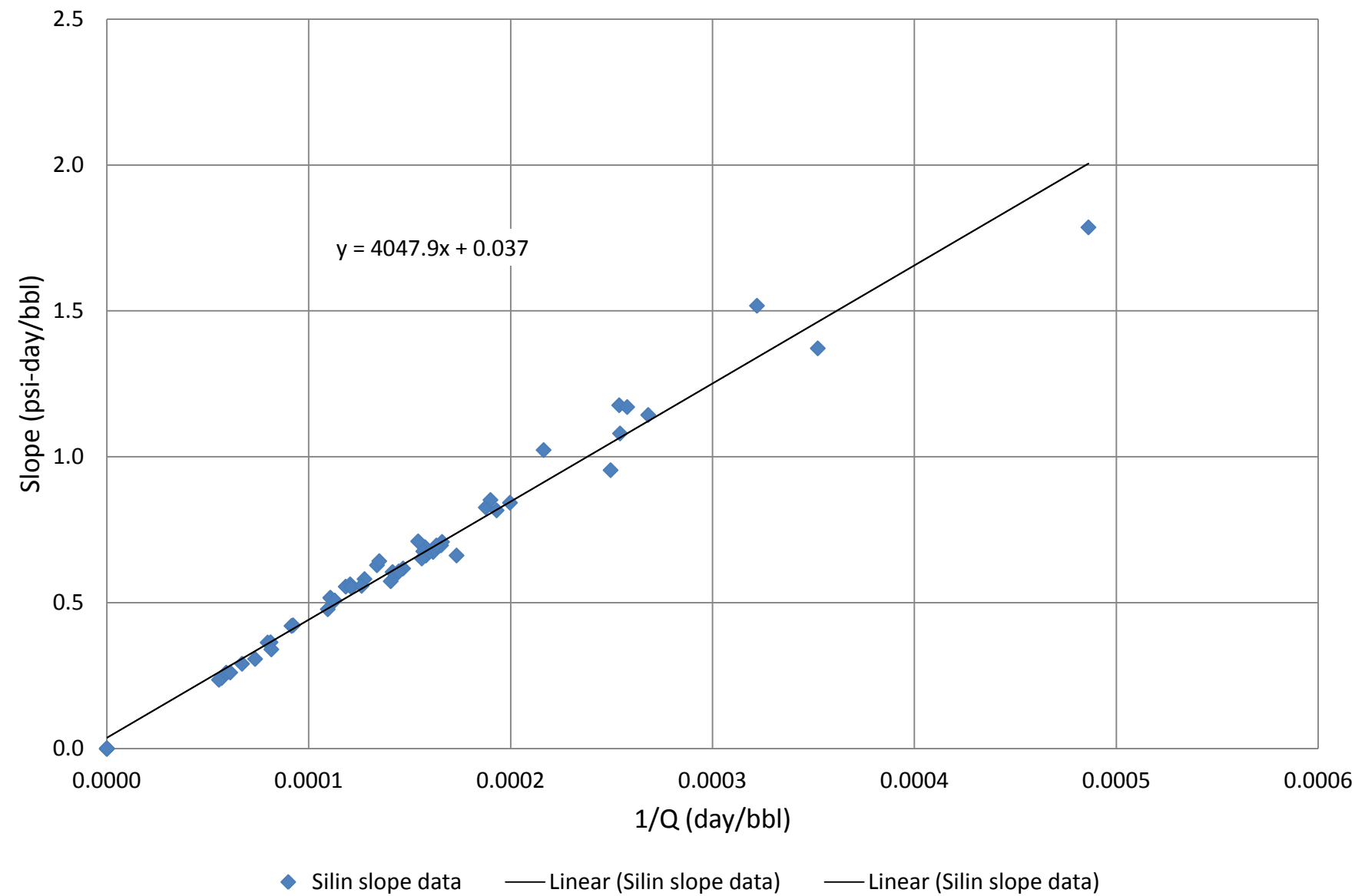
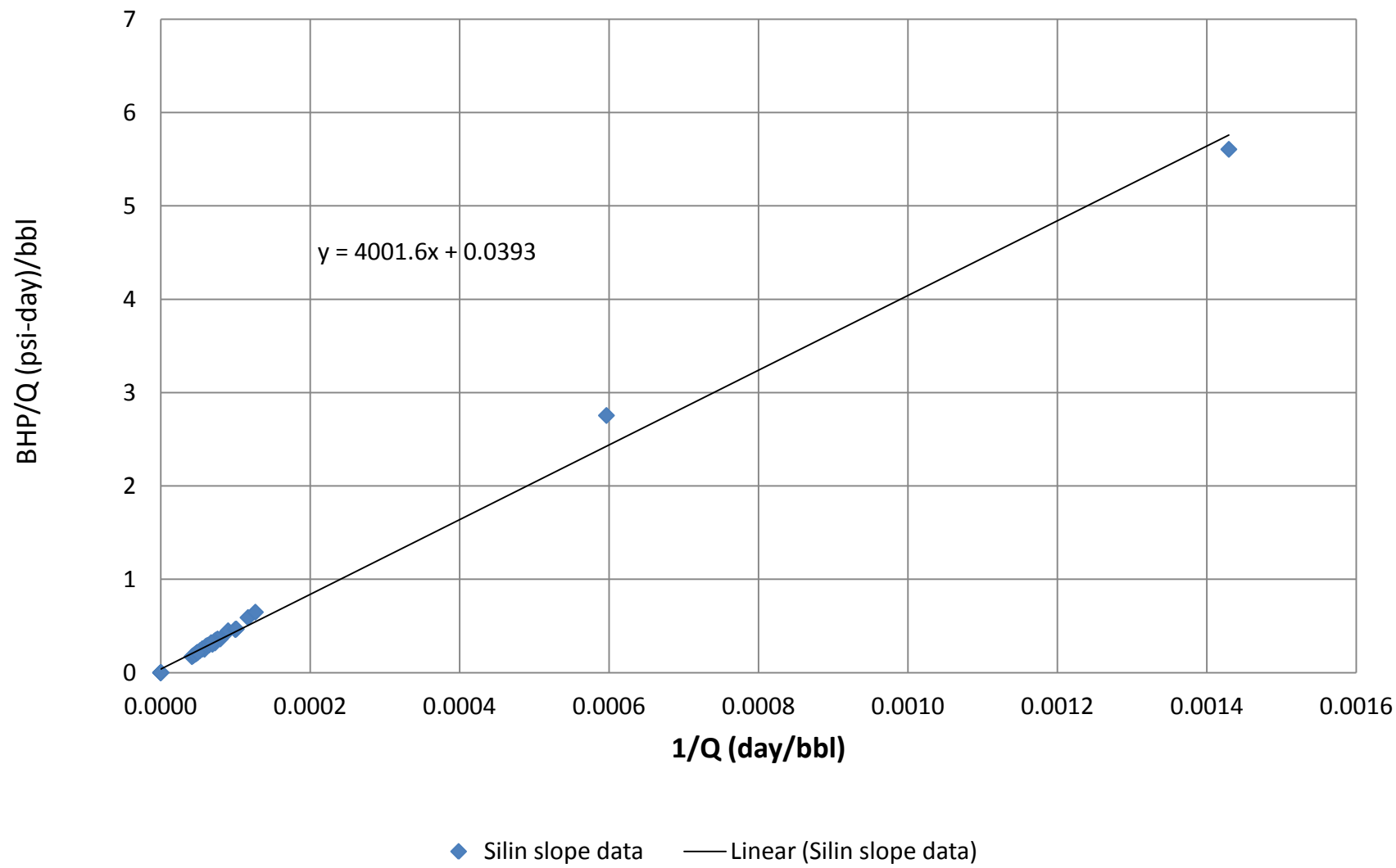
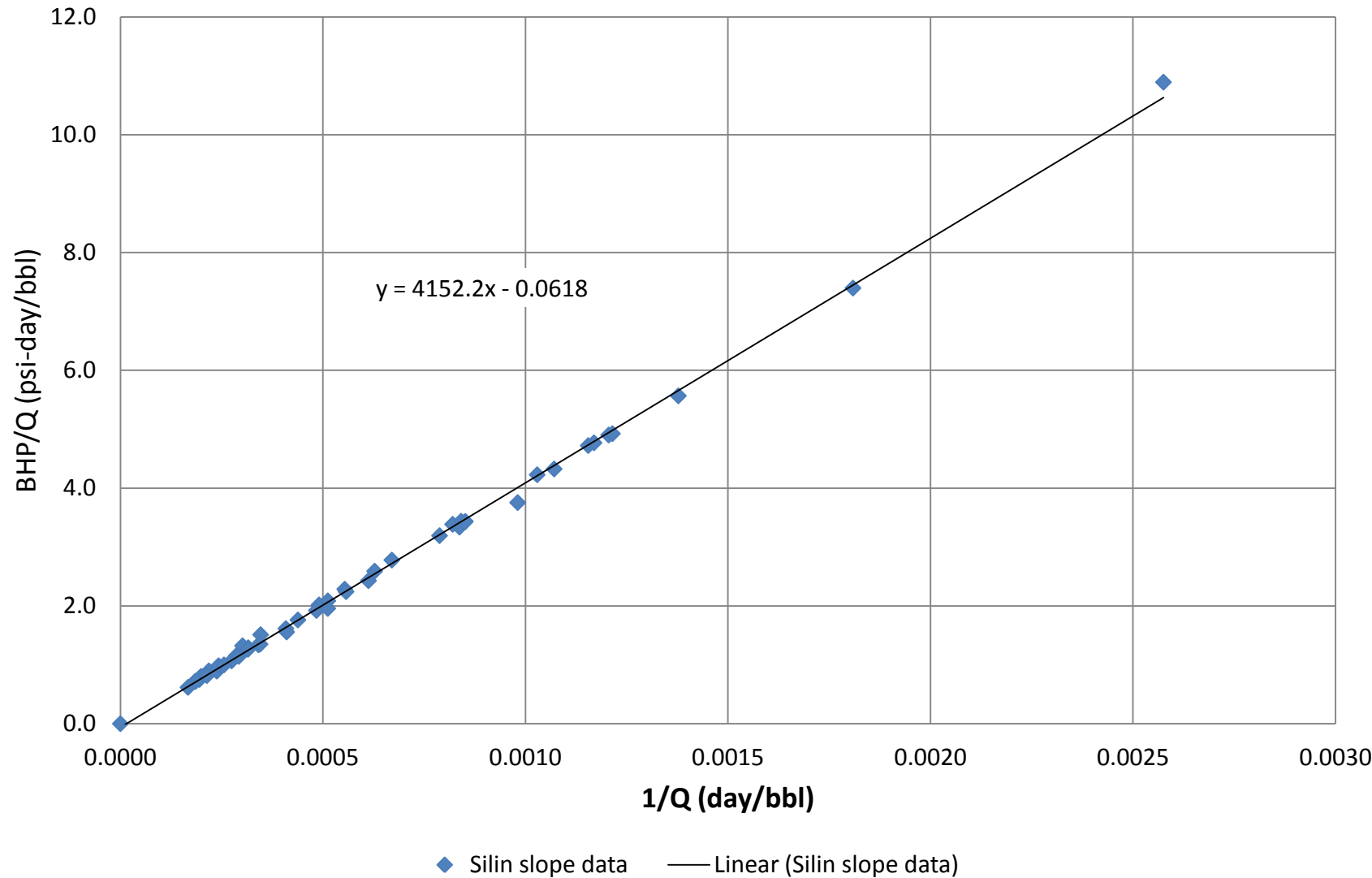


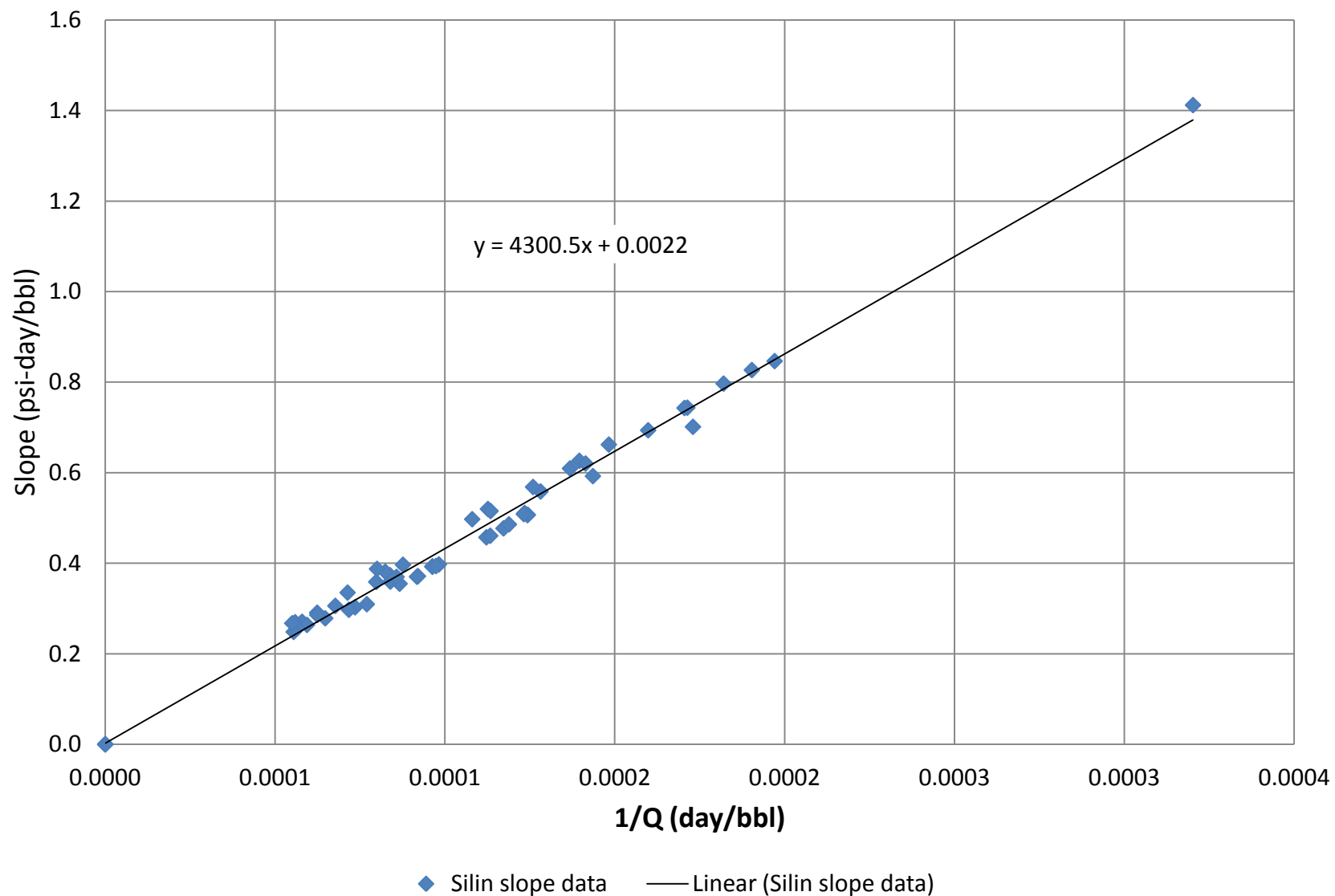
FIGURE D-51: SALTY SWD III SILIN SLOPE PLOT



**FIGURE D-52: CLEBURNE YARD SWD 1 SILIN SLOPE PLOT**



**FIGURE D-53: JOHNSON COUNTY SWD 1 SILIN SLOPE PLOT**



**FIGURE D-54: SPARKS DRIVE SWD 1 TANDEM PLOT**

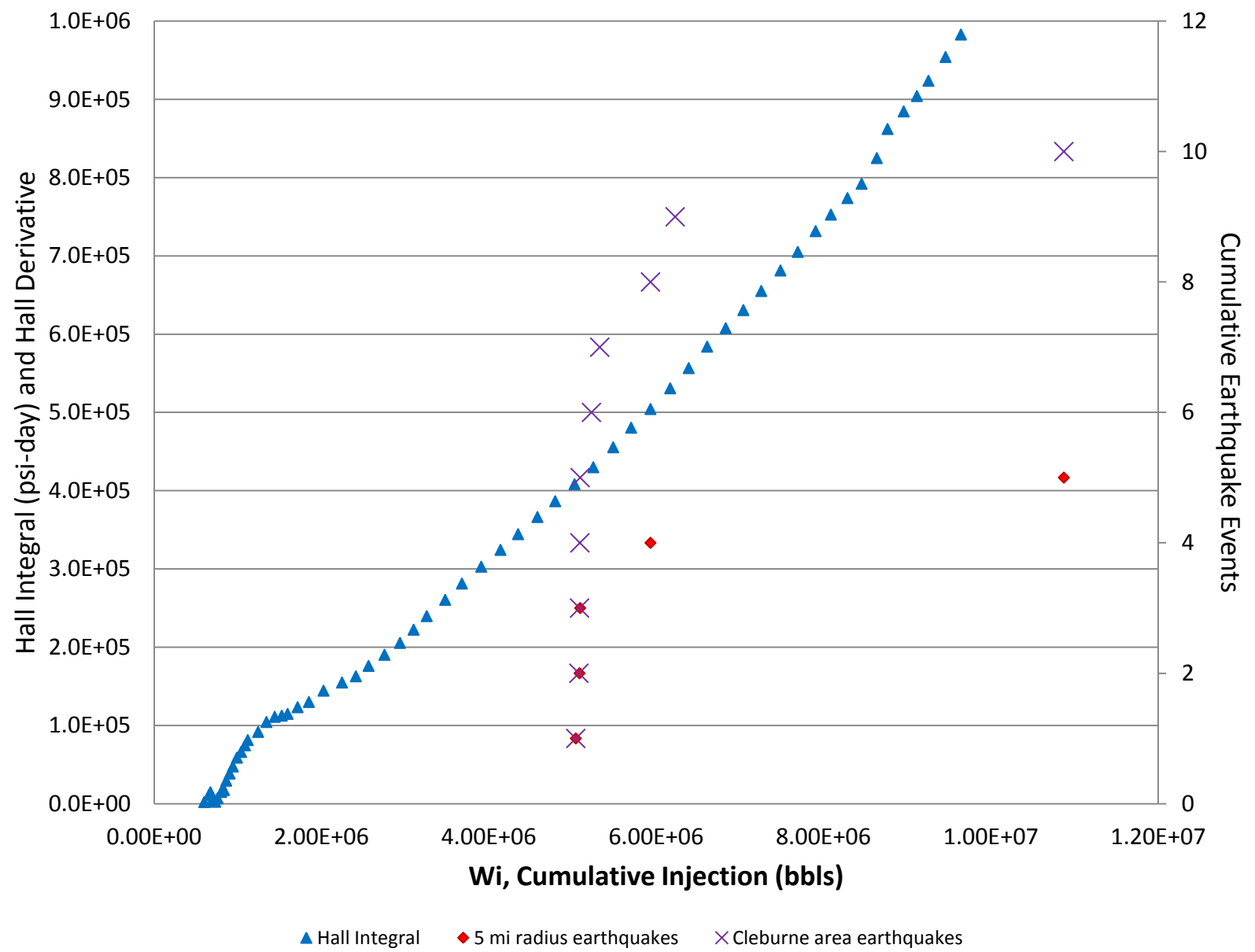
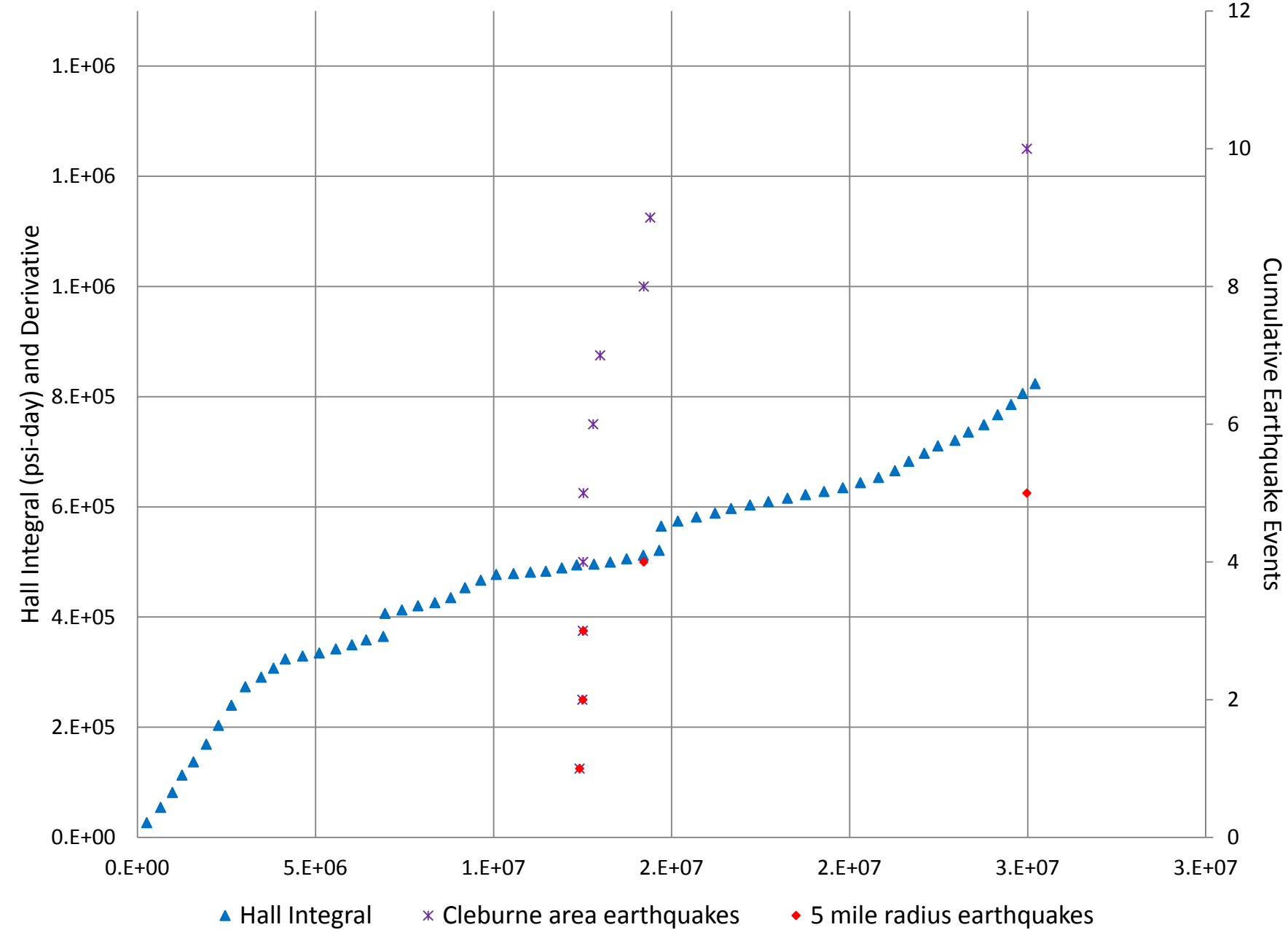


FIGURE D-55 S. MANN SWD 1 TANDEM PLOT



**FIGURE D-56: S. CLEBURNE SWD 1 TANDEM PLOT**

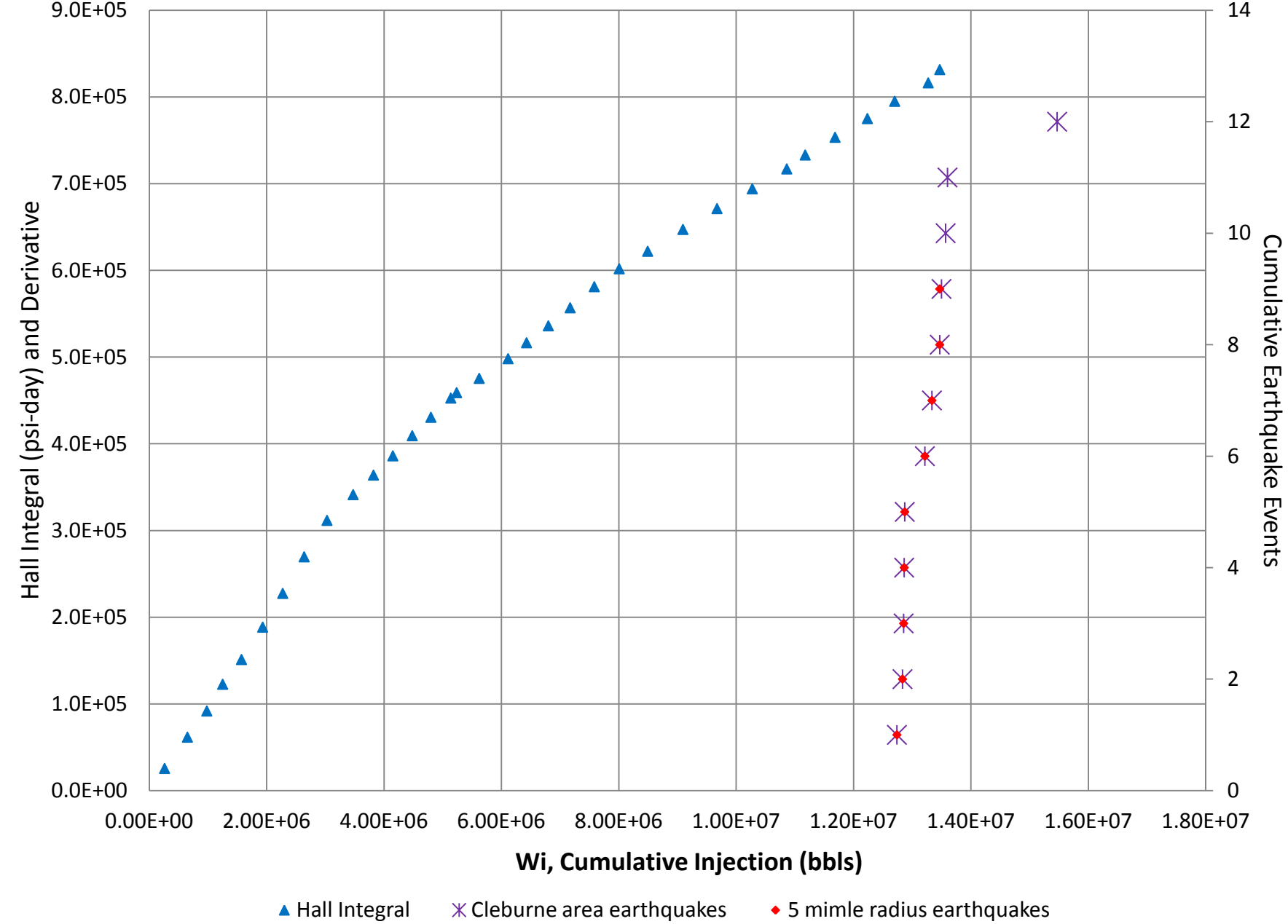




FIGURE D-57: SALTY SWD II TANDEM PLOT

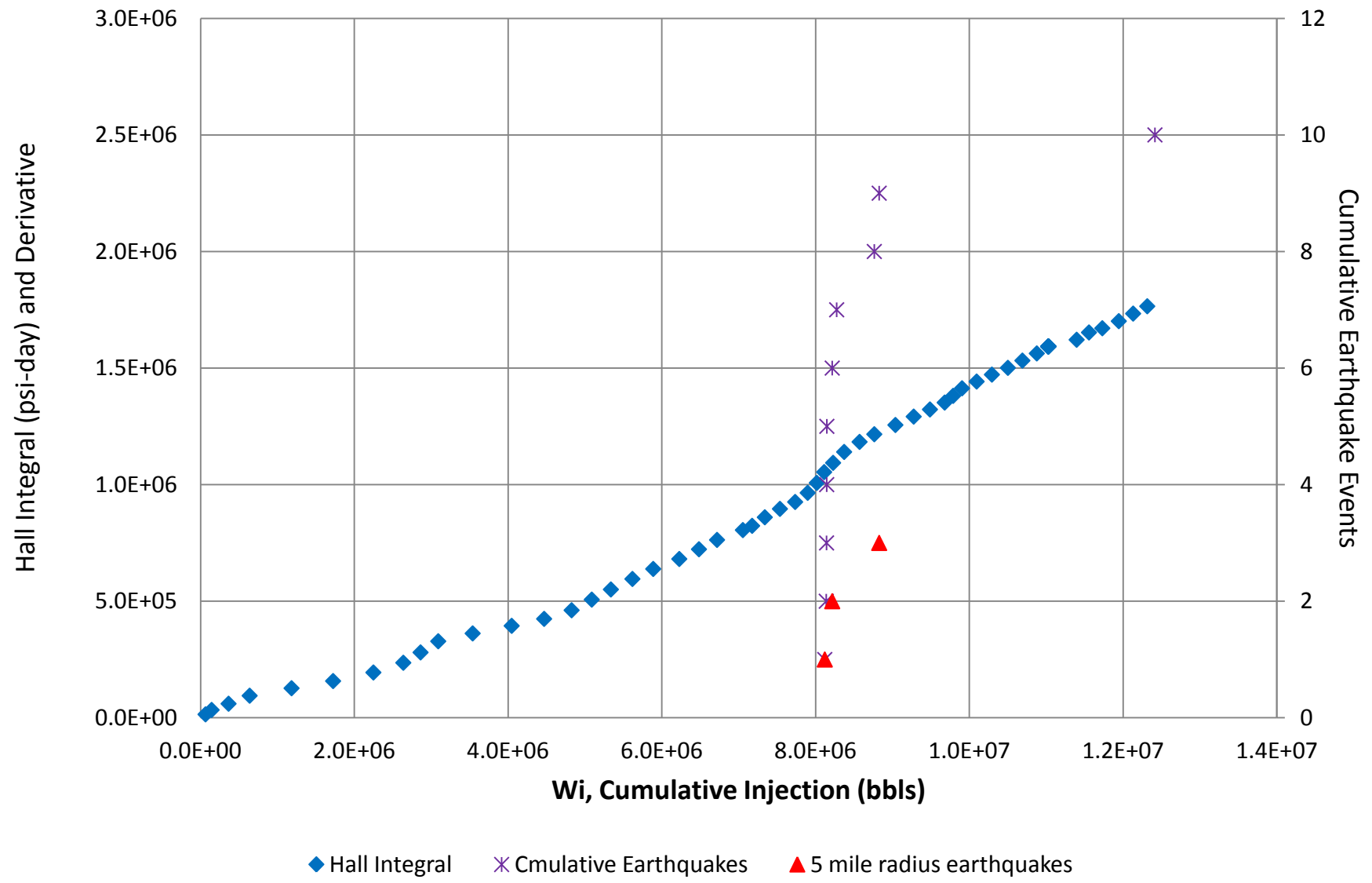
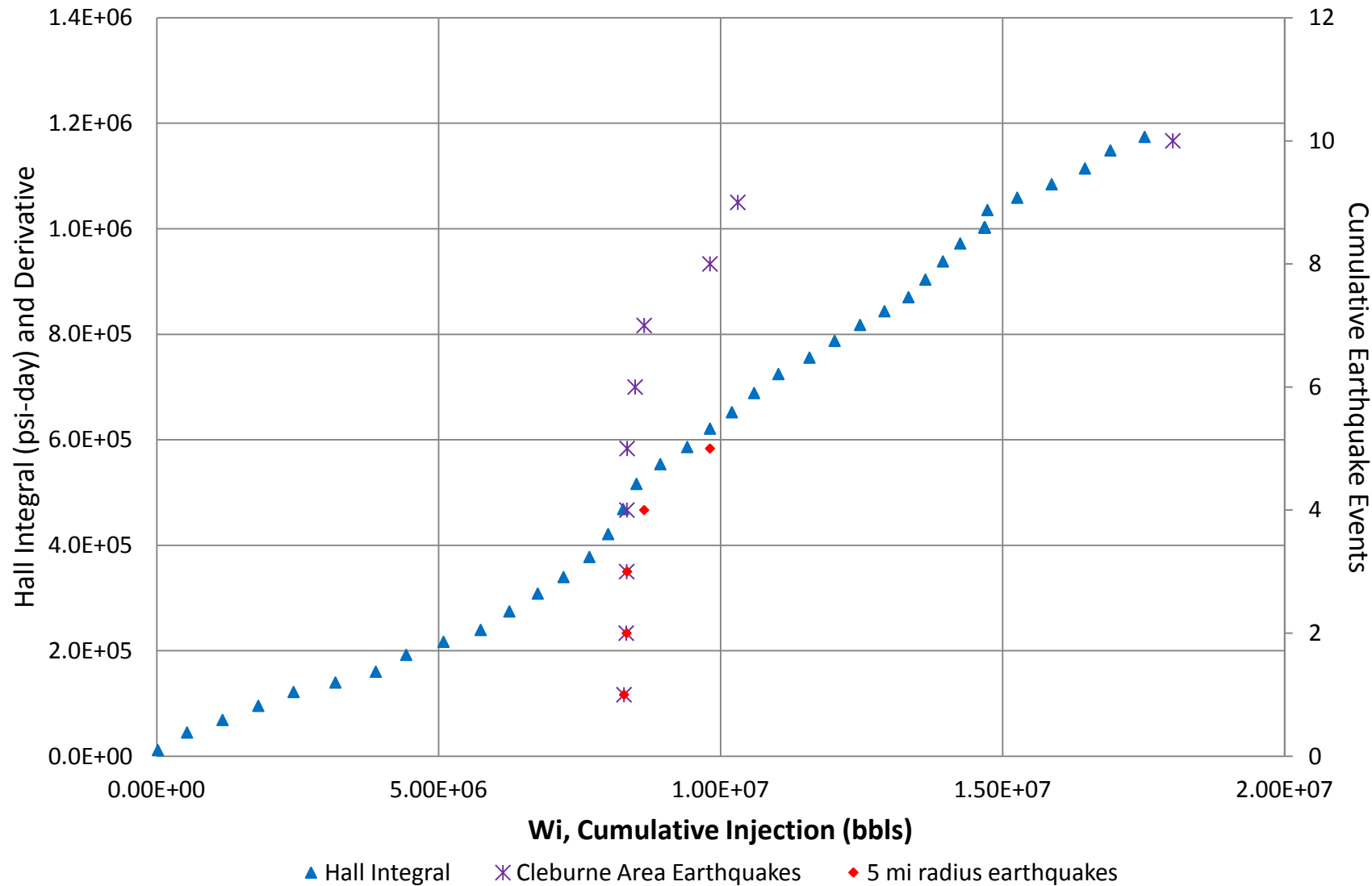


FIGURE D-58: SALTY SWD III TANDEM PLOT



**FIGURE D-59: CLEBURNE YARD 1 TANDEM PLOT**

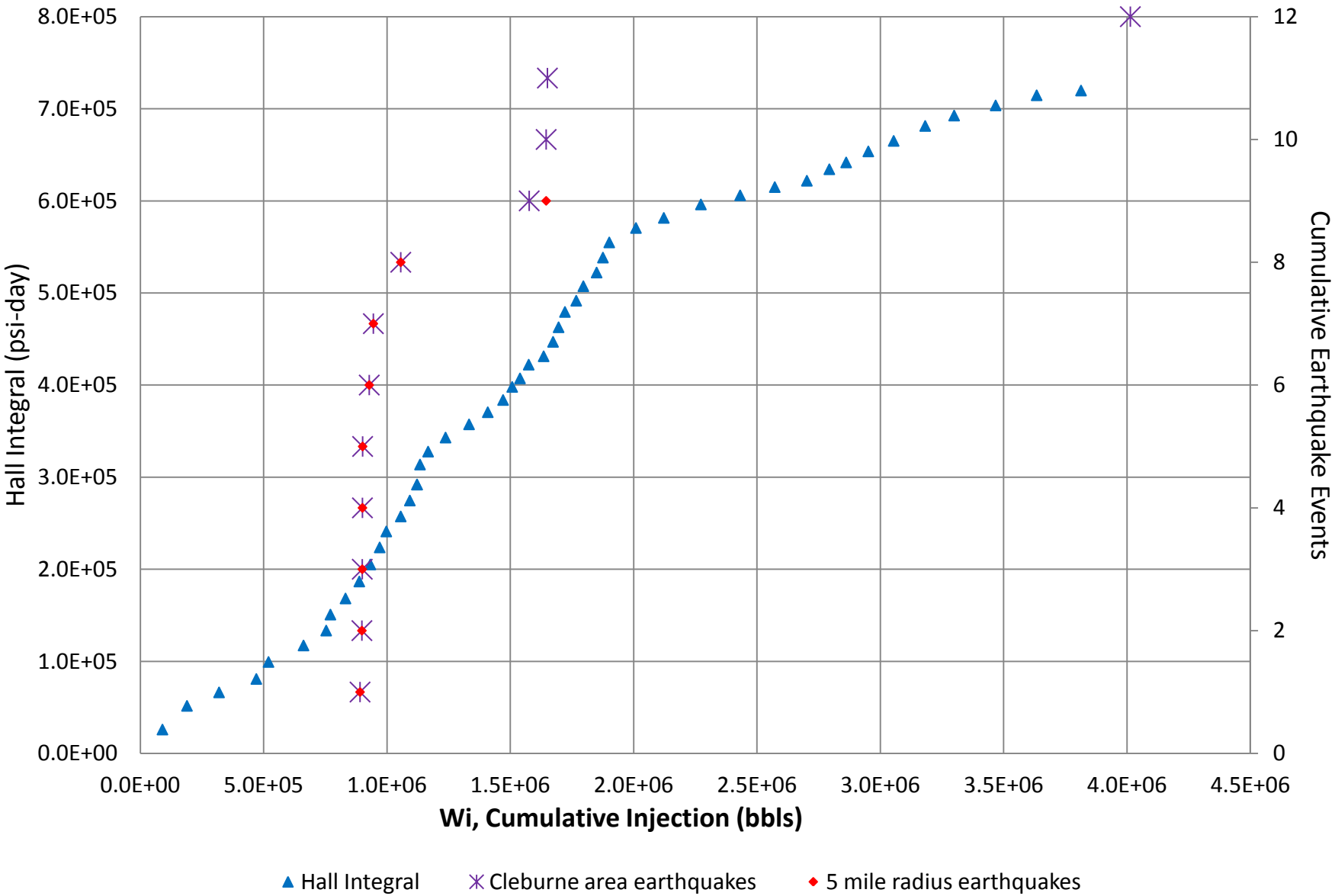


FIGURE D-60: JOHNSON COUNTY SWD 1 TANDEM PLOT

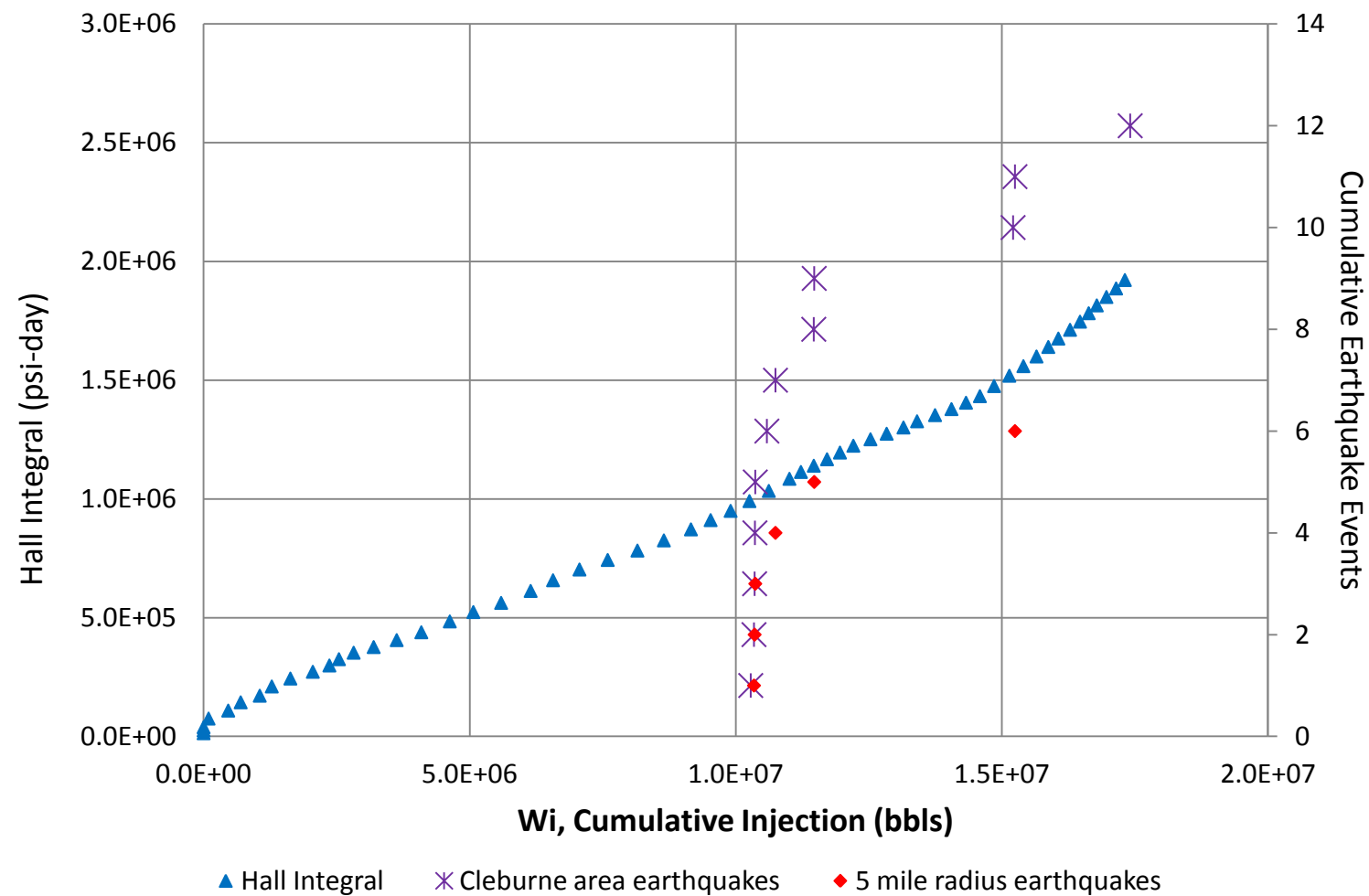


FIGURE D-61: SPARKS SWD 1 2005 FALLOFF TEST OVERVIEW PLOT

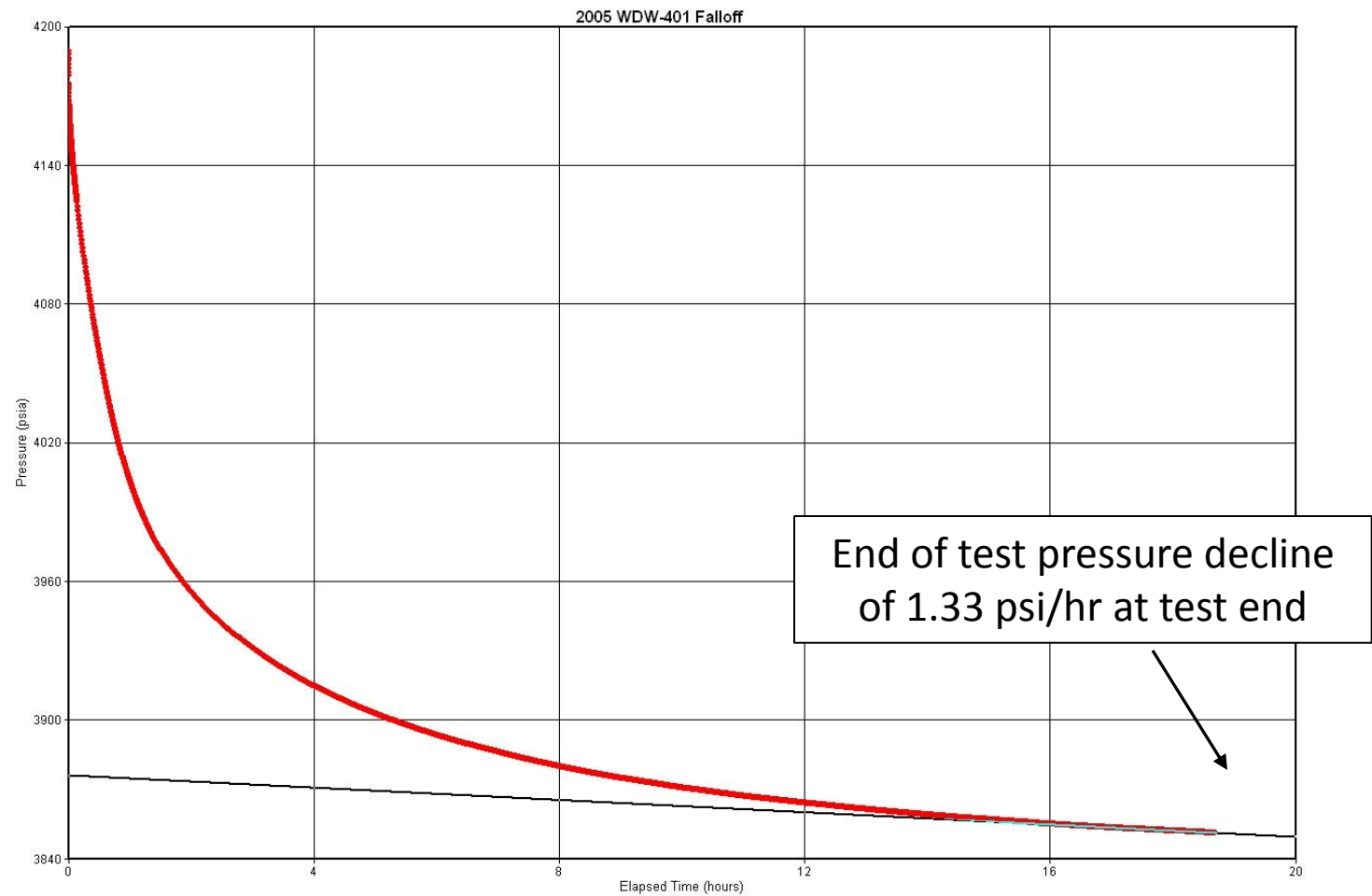
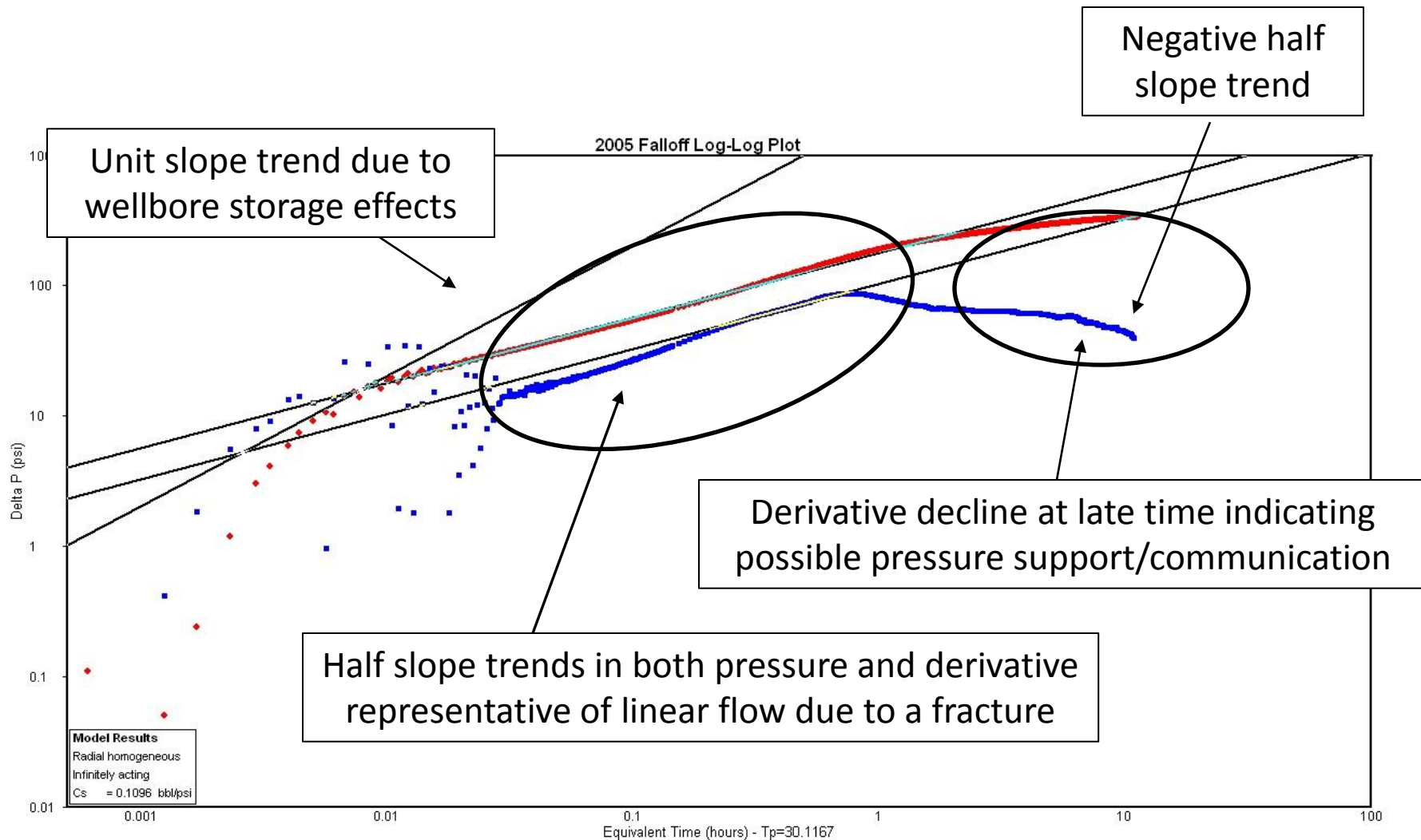


FIGURE D-62: SPARKS DRIVE SWD 1 2005 FALLOFF TEST LOG-LOG PLOT



**FIGURE D-63: SPARKS DRIVE SWD 1 2005 FALLOFF TEST**  
**HOMOGENEOUS RADIAL FLOW TYPE CUVE MATCH**

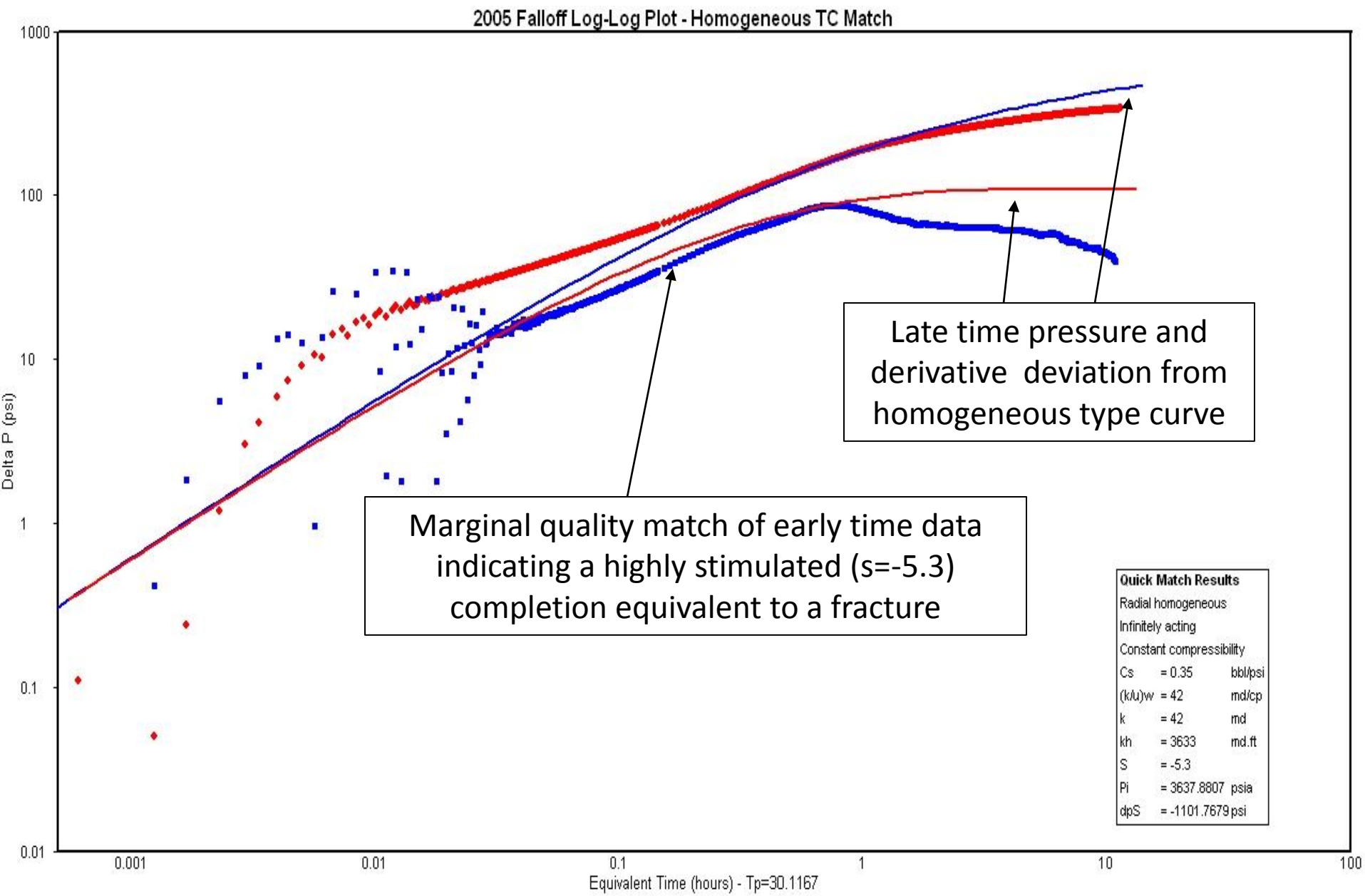


FIGURE D-64: SPARKS DRIVE SWD 1 2005 FALLOFF TEST  
INFINITE CONDUCTIVITY FRACTURE TYPE CURVE MATCH

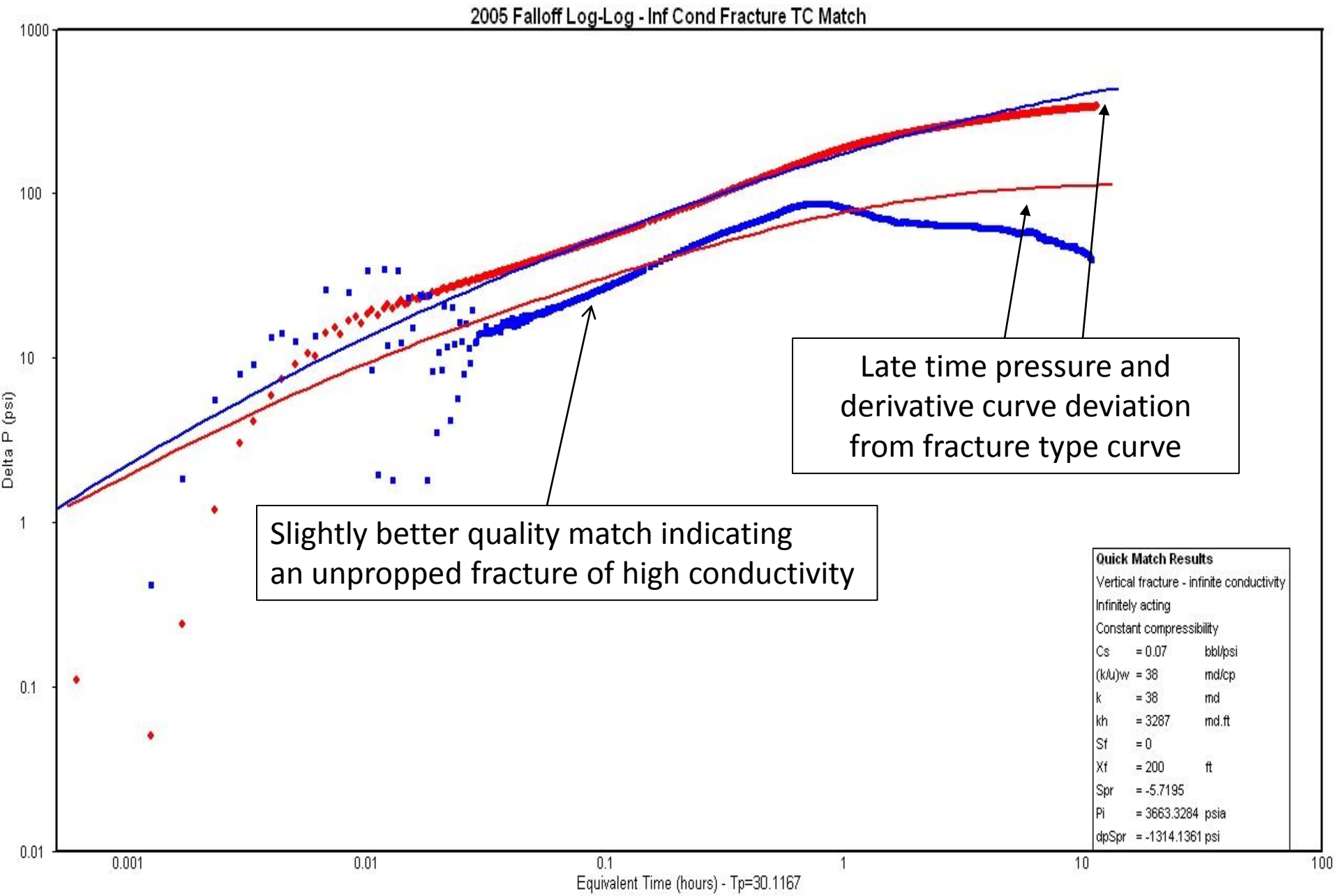
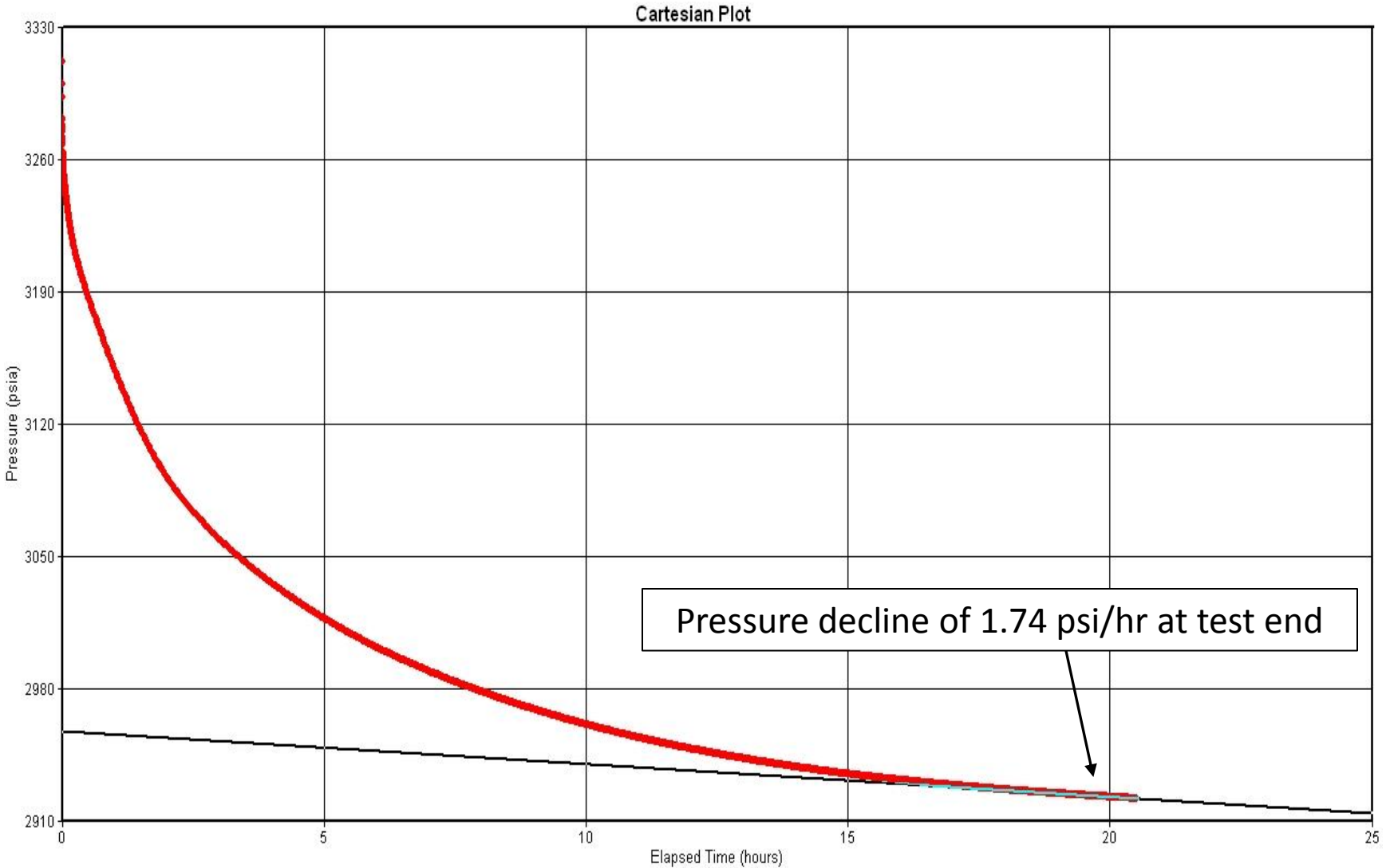
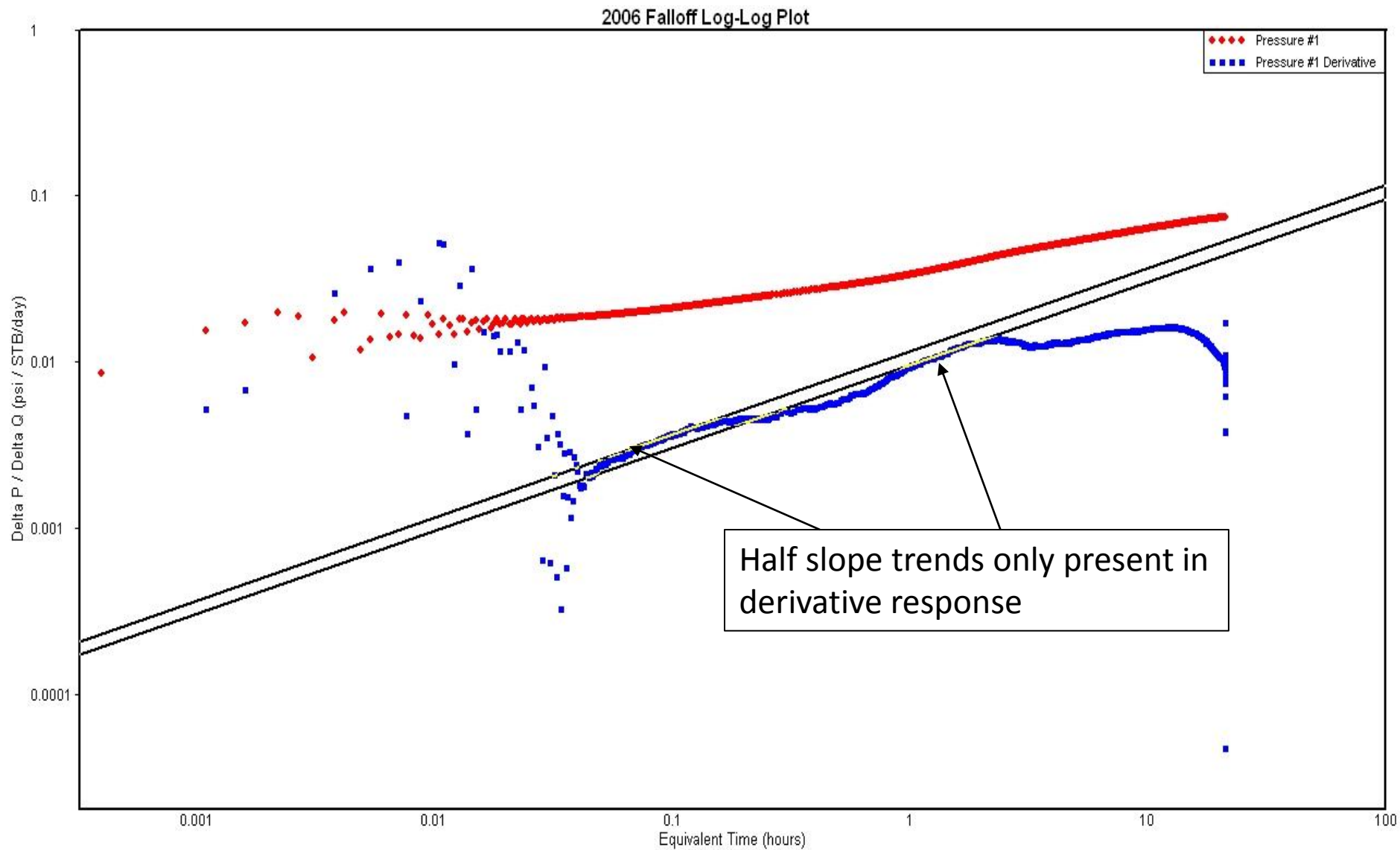




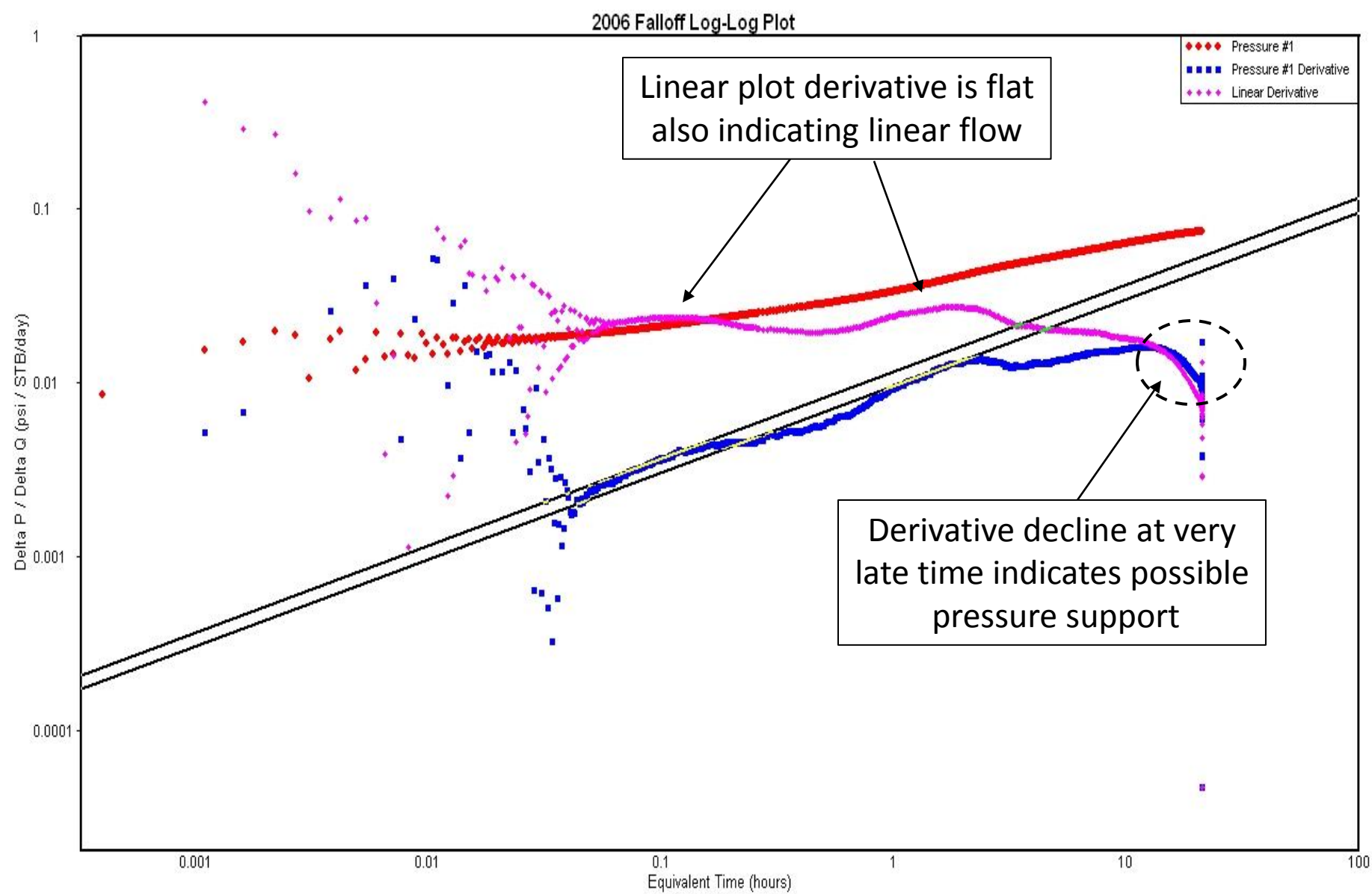
FIGURE D-65: SPARKS DRIVE SWD 1 2006 FALLOFF TEST OVERVIEW PLOT



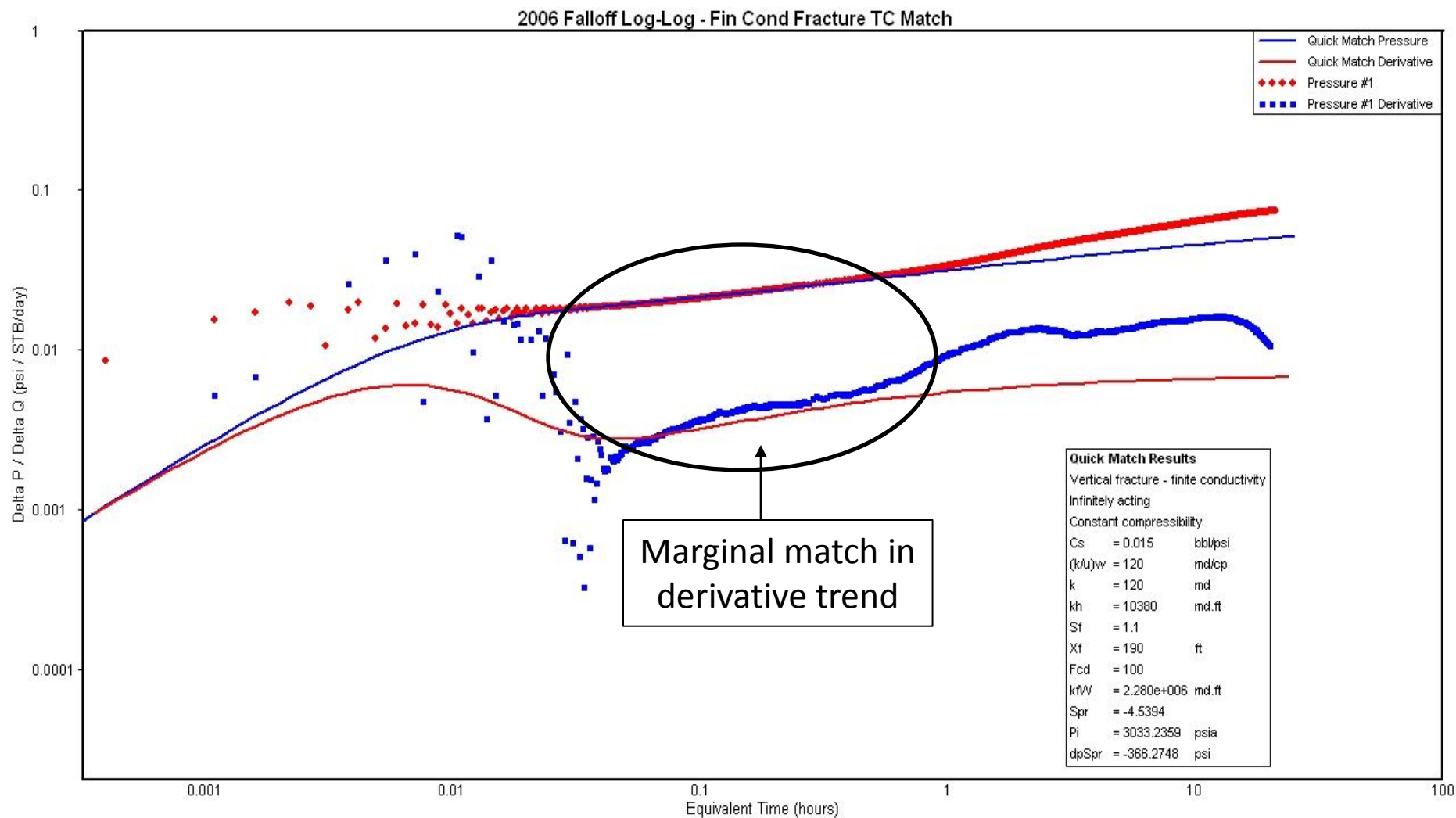
**FIGURE D-66: SPARKS DRIVE SWD 1 2006 FALLOFF TEST LOG-LOG PLOT**



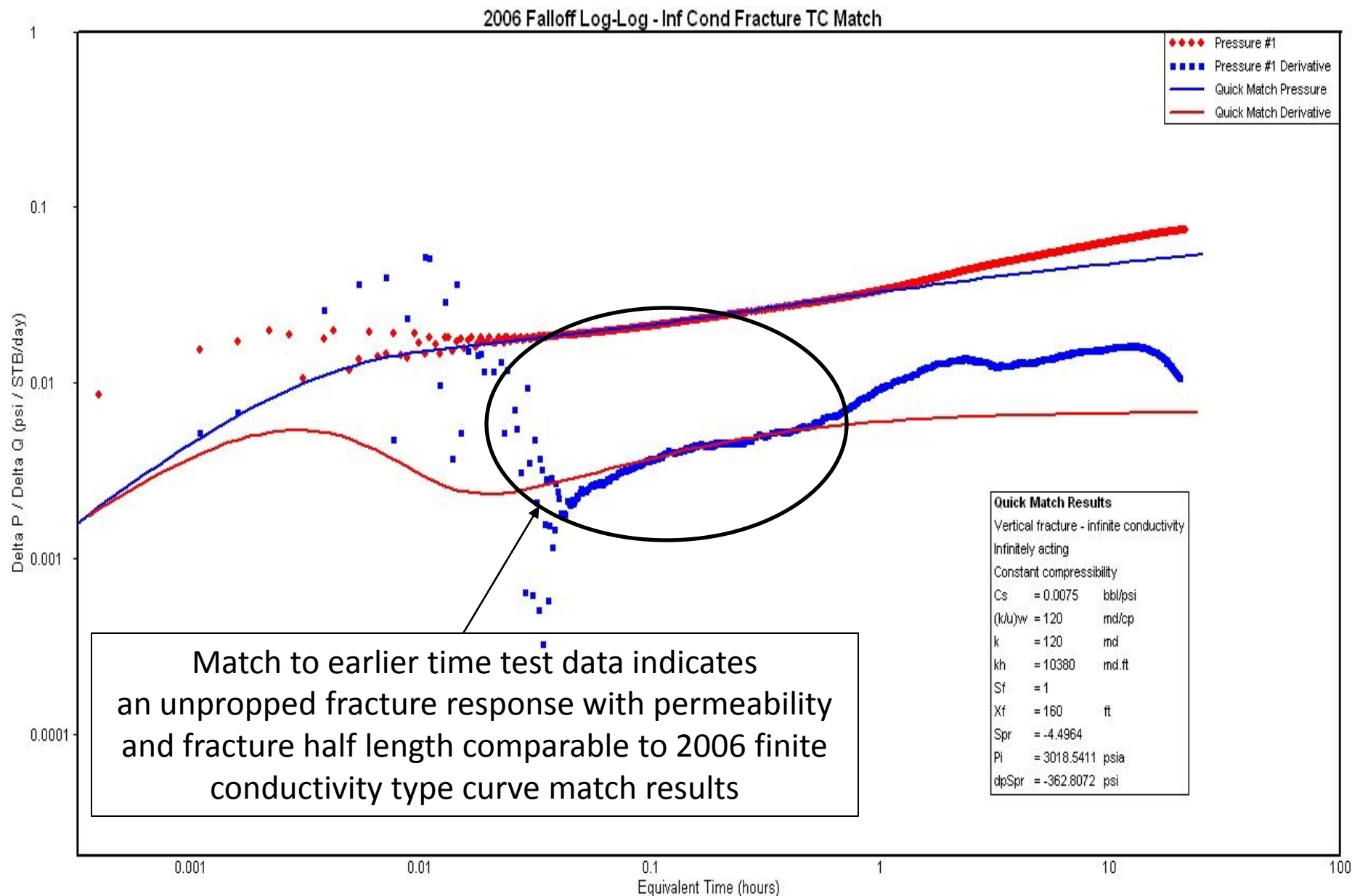
**FIGURE D-67: SPARKS DRIVE SWD 1 2006 FALLOFF TEST**  
**LOG-LOG PLOT WITH LINEAR ( $\sqrt{\text{TIME}}$ ) DERIVATIVE**



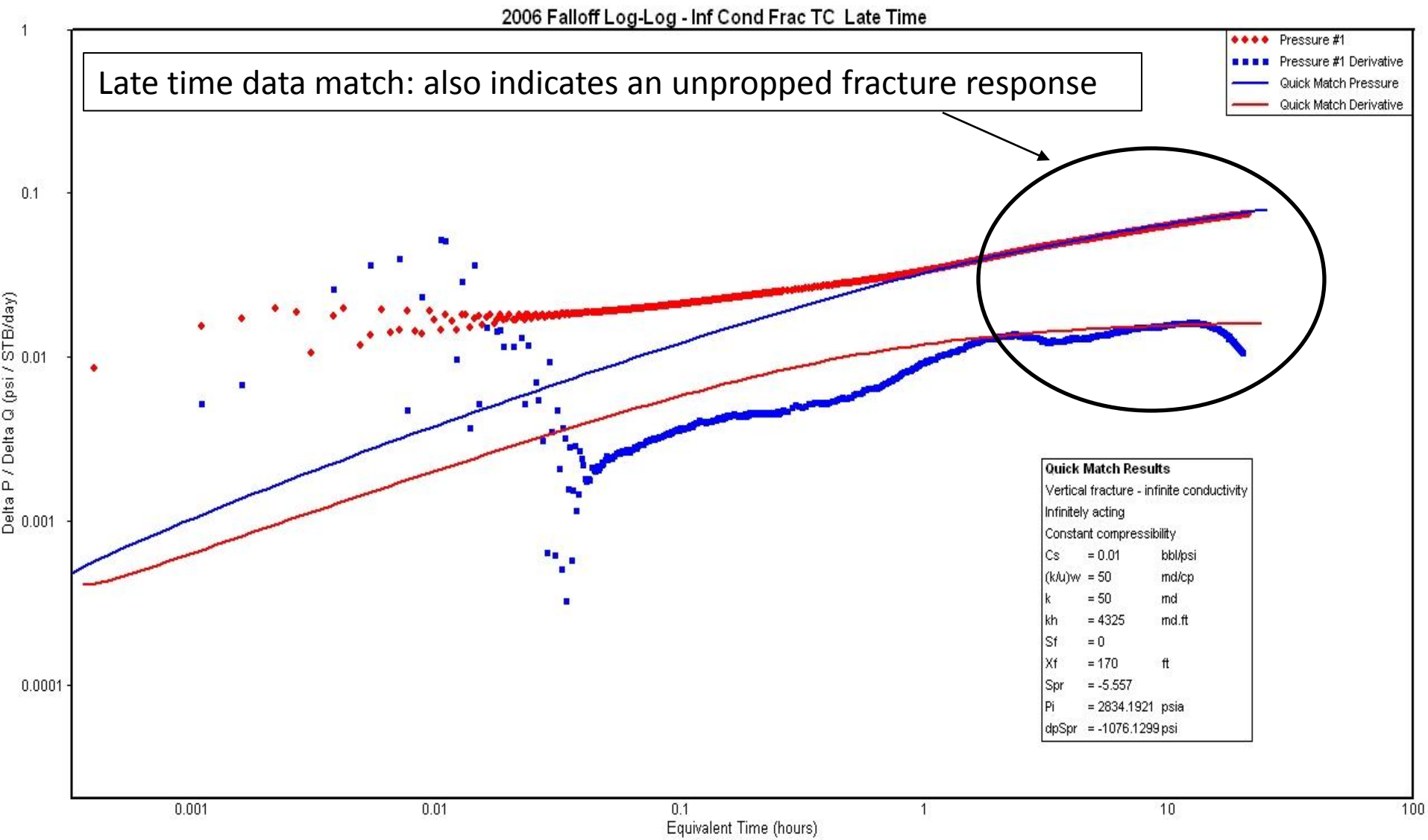
**FIGURE D-68: SPARKS DRIVE SWD 1 2006 FALLOFF TEST**  
**FINITE CONDUCTIVITY FRACTURE TYPE CURVE MATCH**



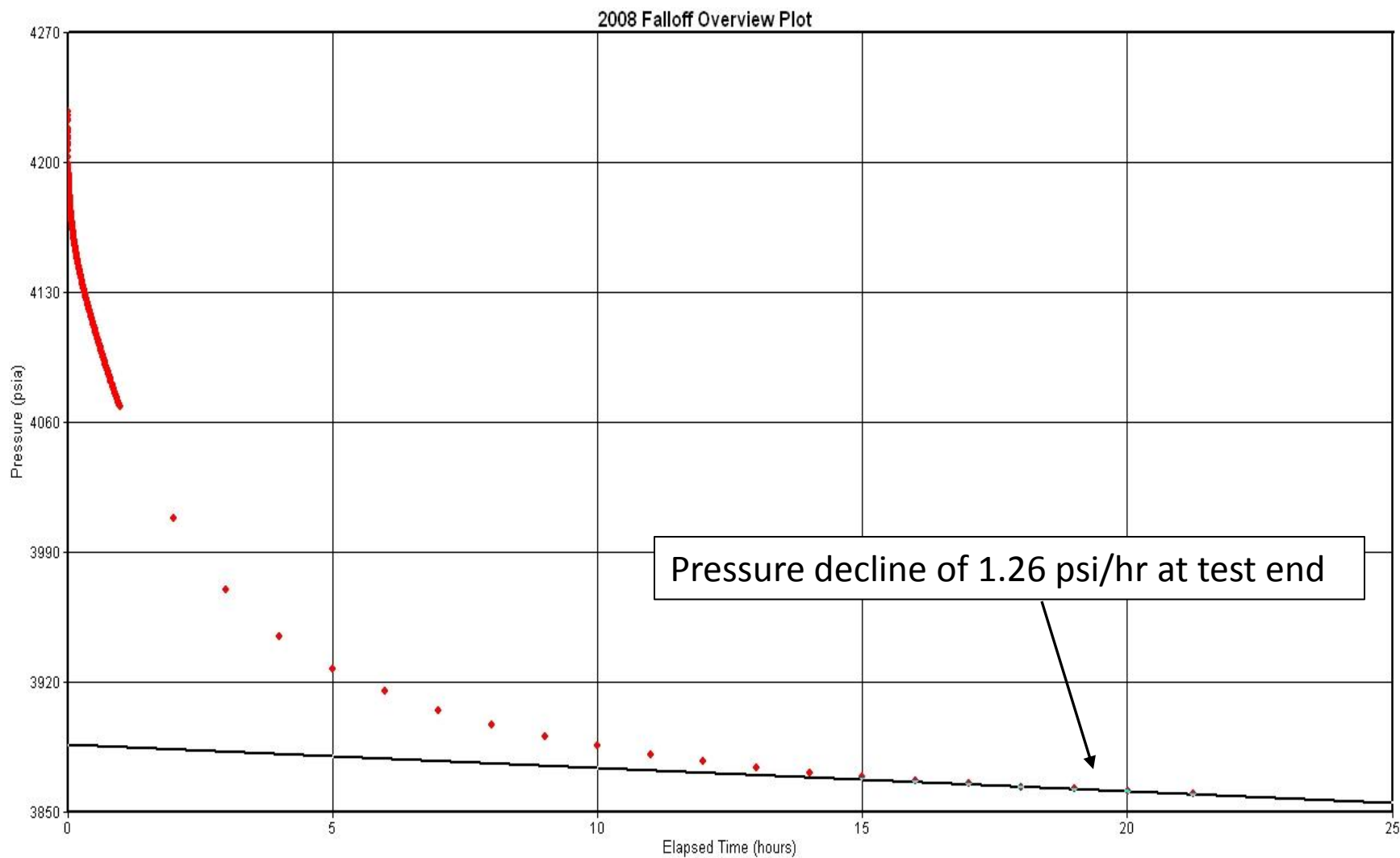
**FIGURE D-69: SPARKS DRIVE SWD 1 2006 FALLOFF TEST**  
**INFINITE CONDUCTIVITY FRACTURE TYPE CURVE MATCH**



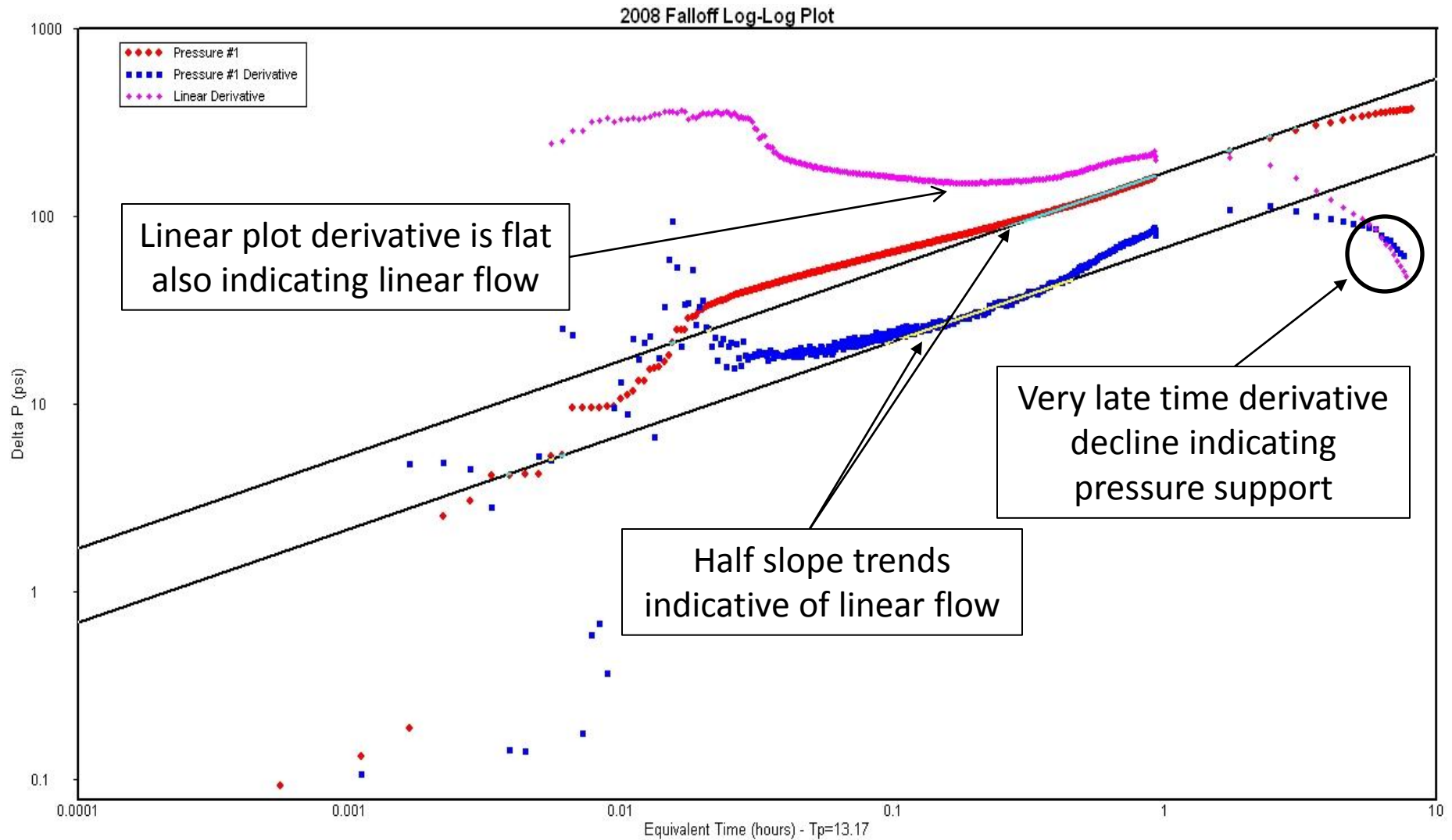
**FIGURE D-70: SPARKS DRIVE SWD 1 2006 FALLOFF TEST**  
**INFINITE CONDUCTIVITY TYPE CURVE MATCH TO LATE TIME DATA**



**FIGURE D-71: SPARKS DRIVE SWD 1 2008 FALLOFF TEST OVERVIEW PLOT**

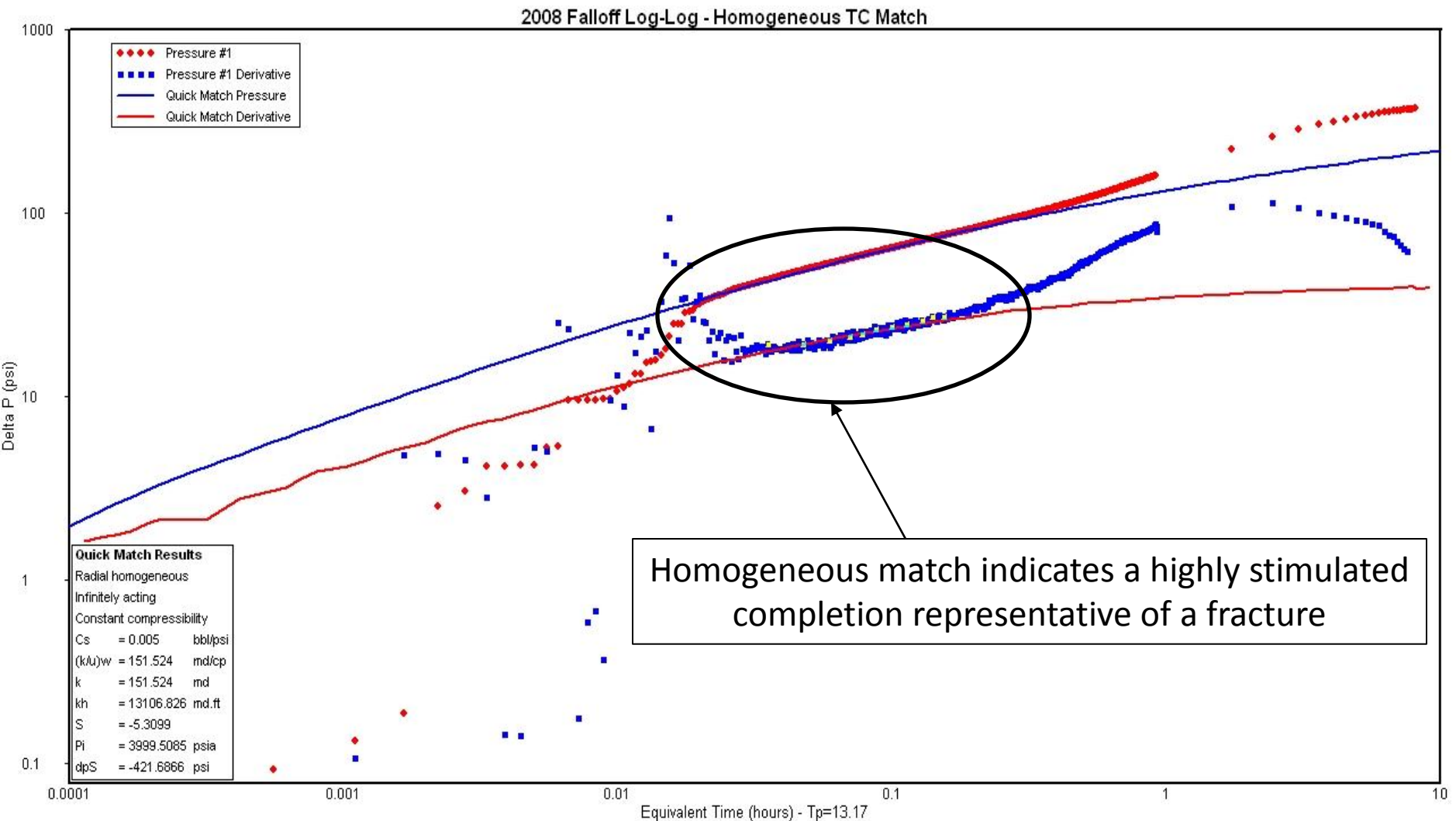


**FIGURE D-72: SPARKS DRIVE SWD 1 2008 FALLOFF TEST LOG-LOG PLOT**

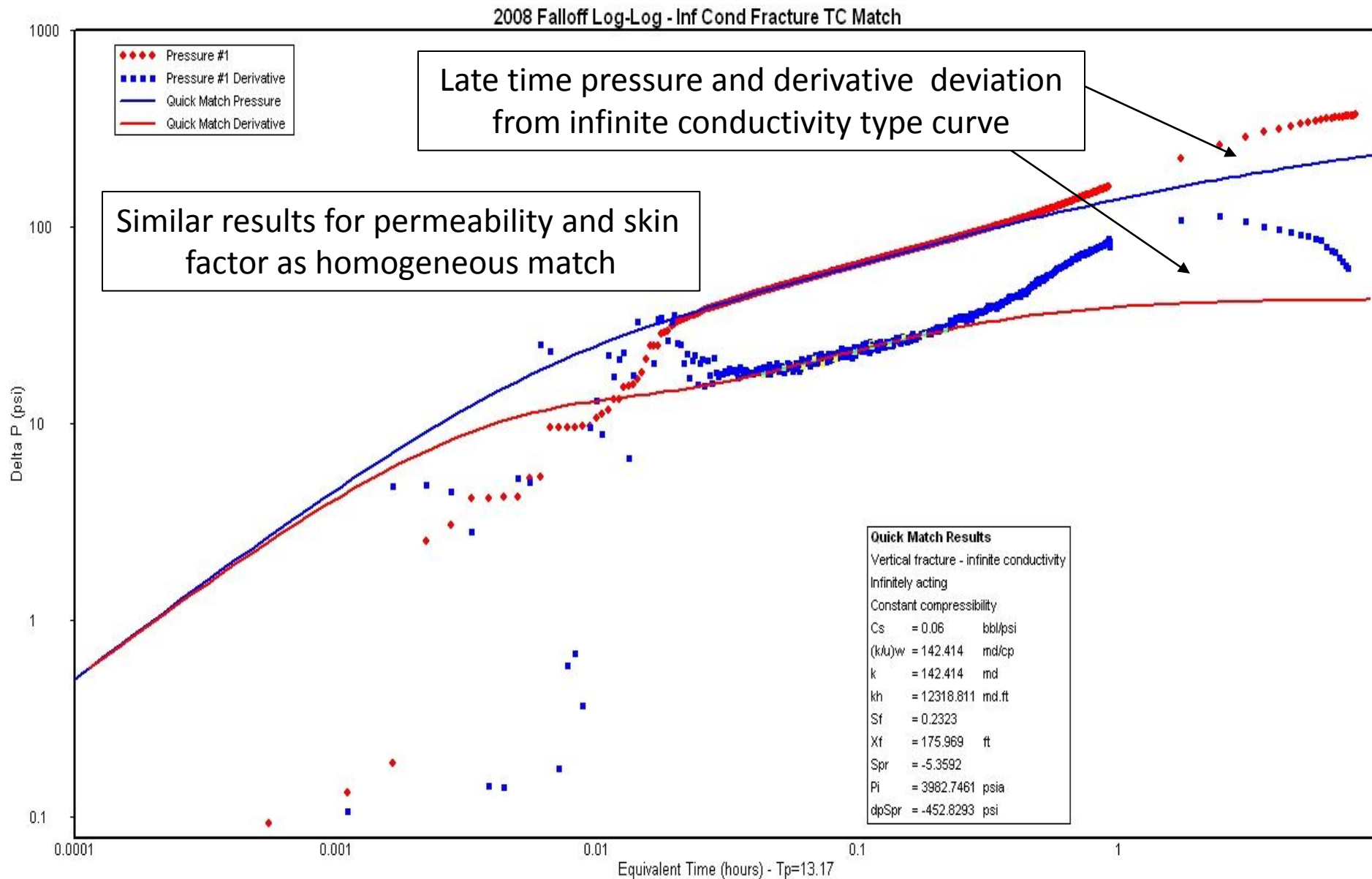




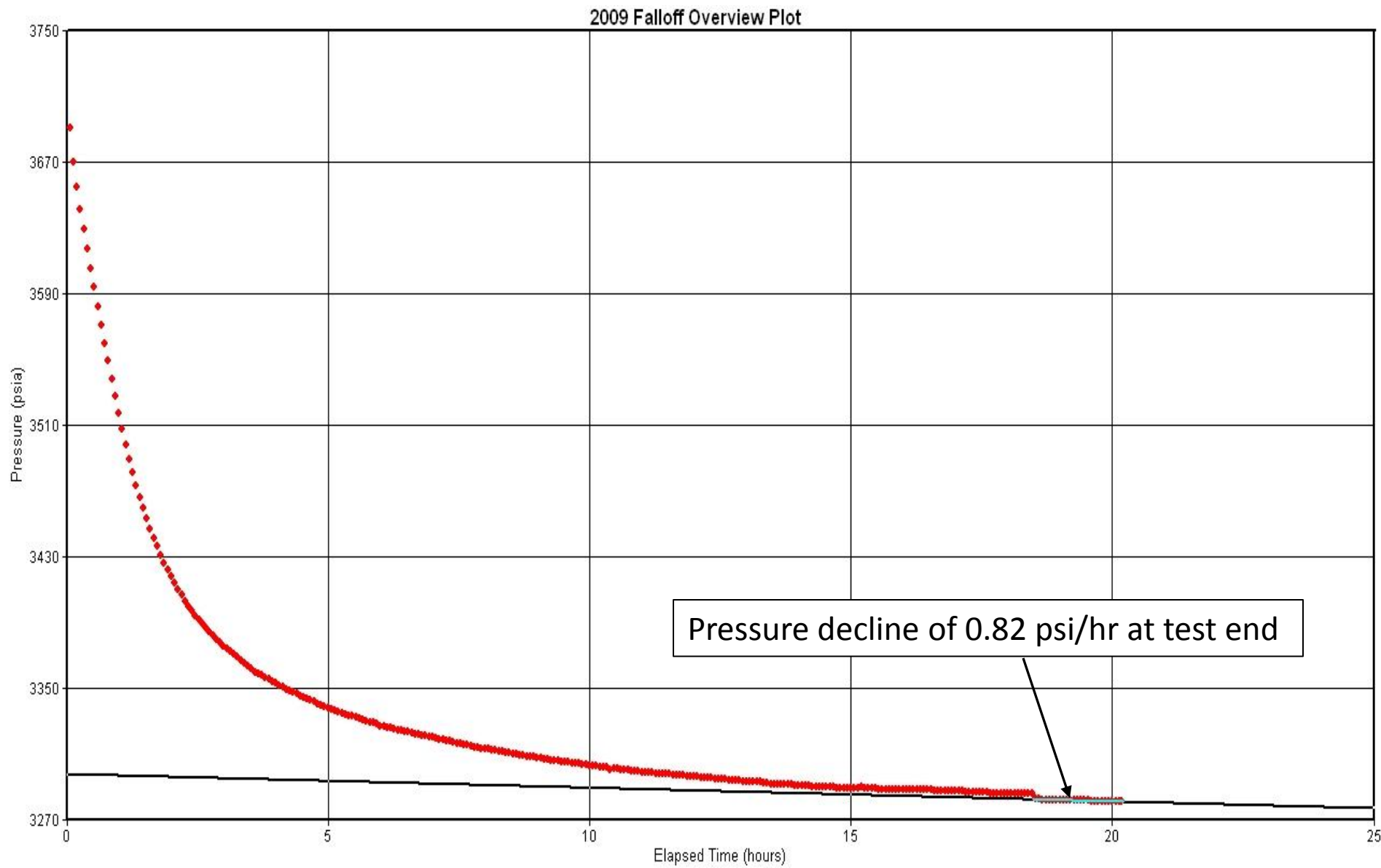
**FIGURE D-73: SPARKS DRIVE SWD 1 2008 FALLOFF TEST**  
**HOMOGENEOUS RESERVIOR TYPE CURVE MATCH**



**FIGURE D-74: SPARKS DRIVE SWD 1 2008 FALLOFF LOG-LOG PLOT**  
**INFINITE CONDUCTIVITY FRACTURE TYPE CURVE MATCH**



**FIGURE D-75: SPARKS DRIVE SWD 1 2009 FALLOFF TEST OVERVIEW PLOT**



**FIGURE D-76: SPARKS DRIVE SWD 1 2009 FALLOFF TEST LOG-LOG PLOT**

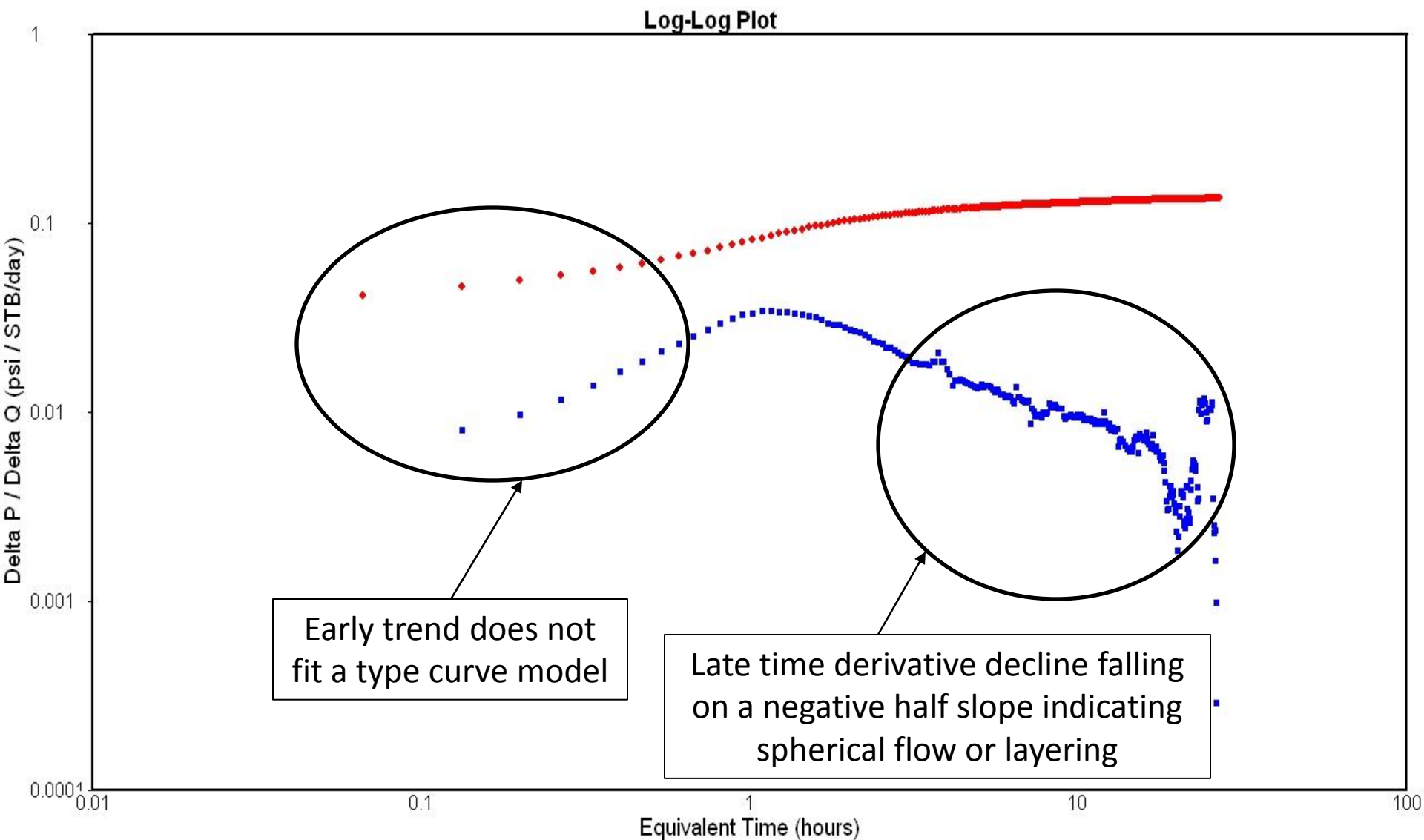
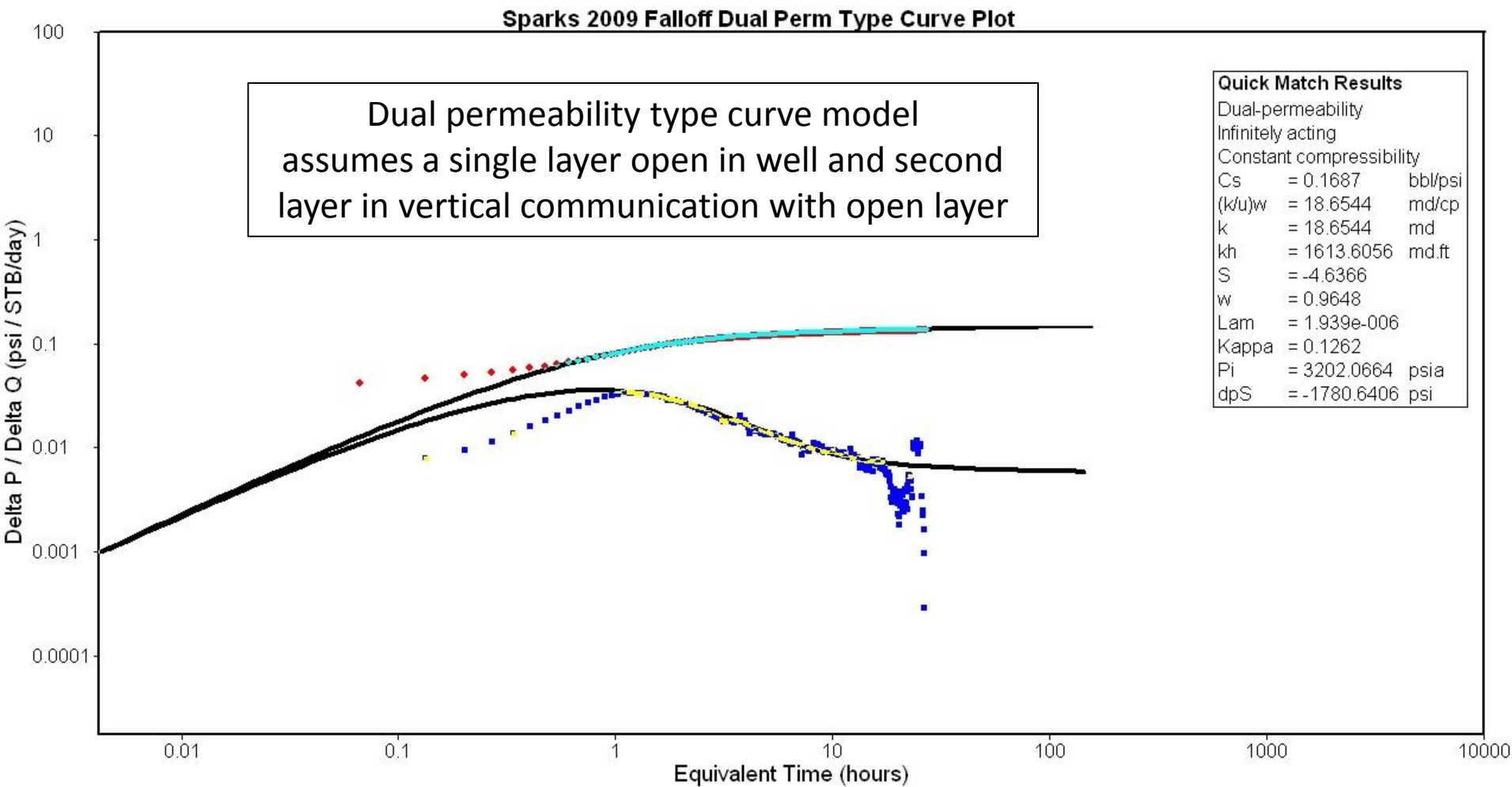
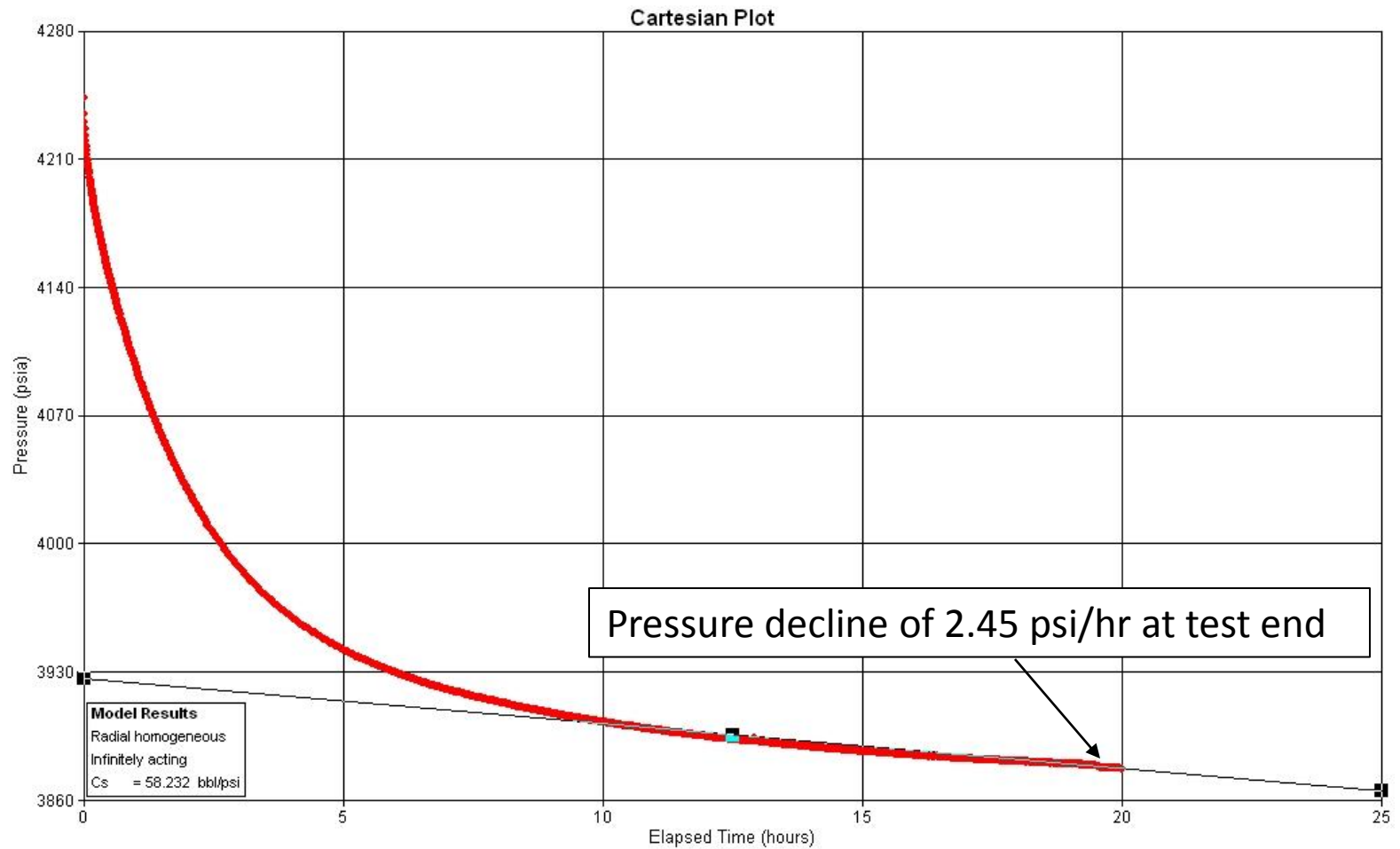


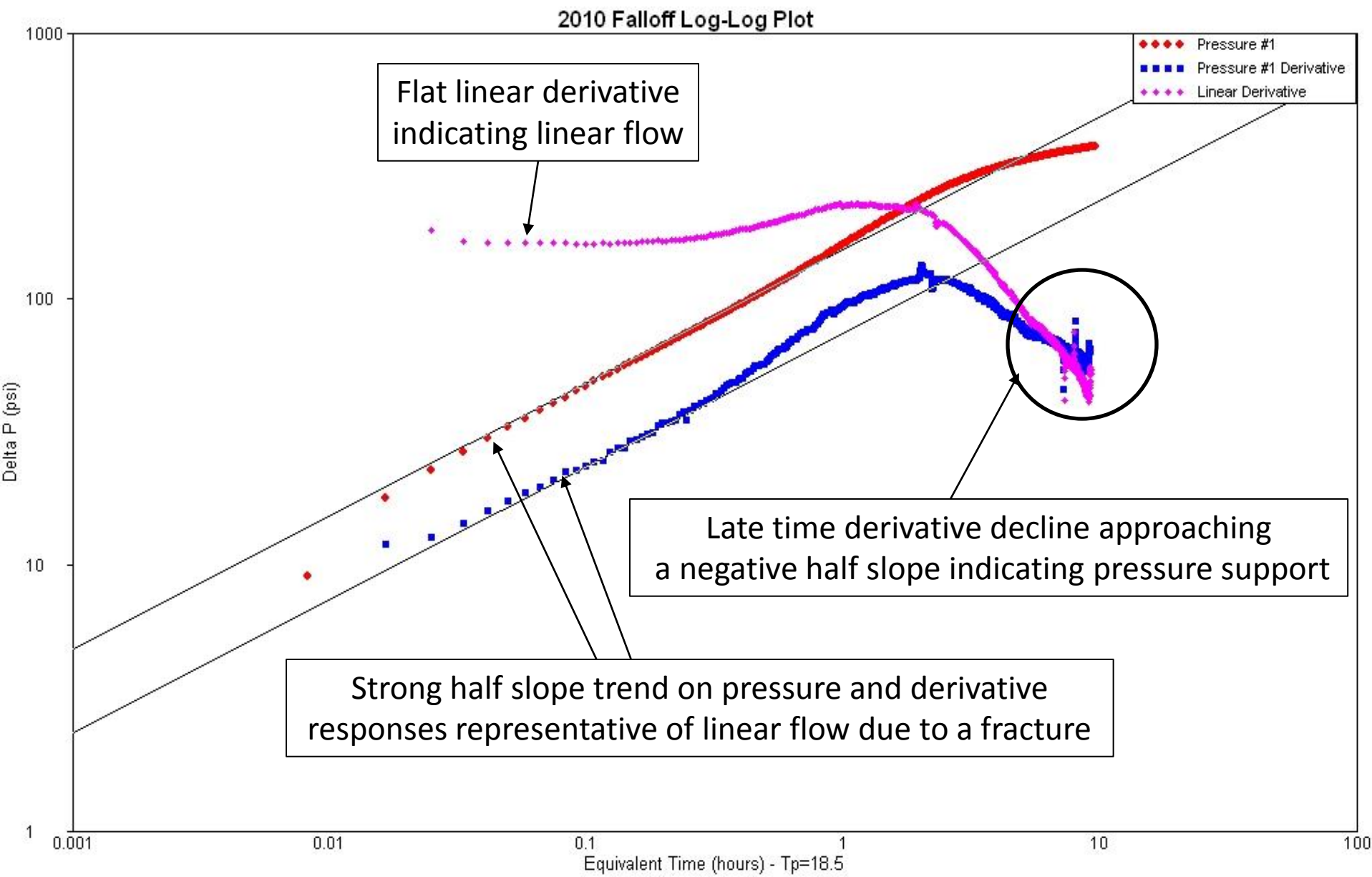
FIGURE D-77: SPARKS DRIVE SWD 1 2009 FALLOFF TEST LOG-LOG PLOT  
DUAL PERMEABILITY MODEL TYPE CURVE MATCH



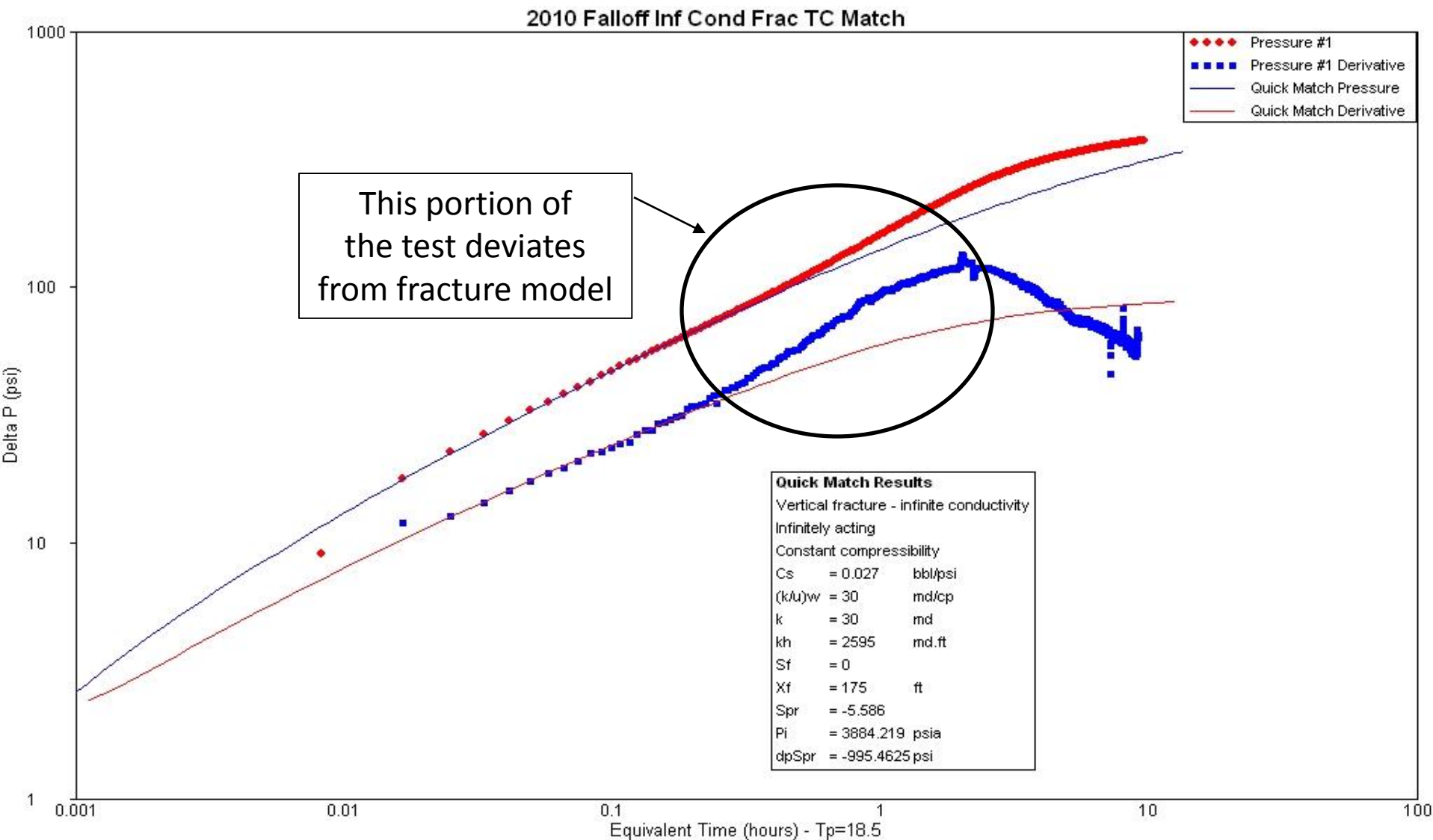
**FIGURE D-78: SPARKS DRIVE SWD 1 2010 FALLOFF TEST OVERVIEW PLOT**



**FIGURE D-79: SPARKS DRIVE SWD 1 2010 FALLOFF TEST LOG-LOG PLOT**

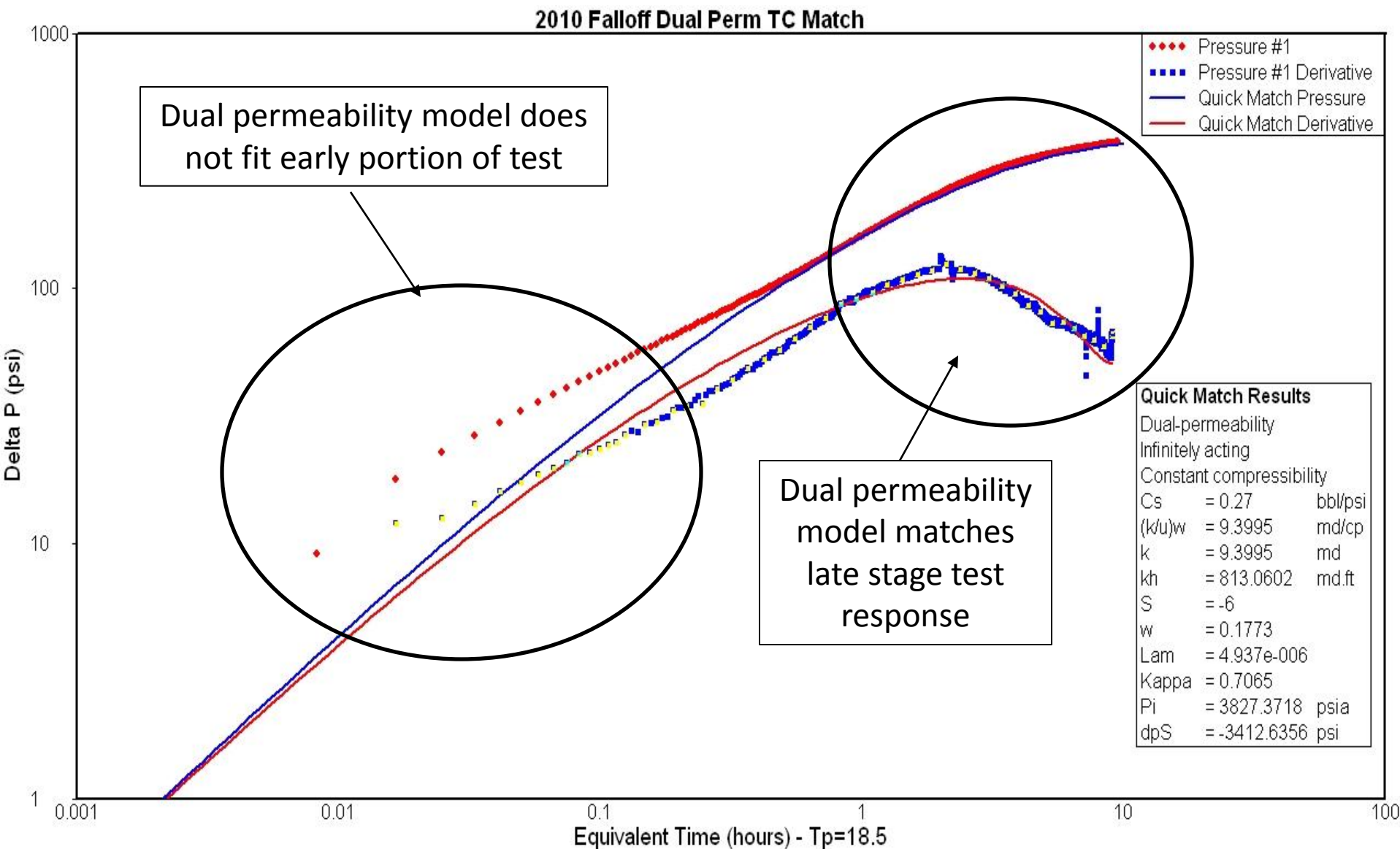


**FIGURE D-80: SPARKS DRIVE SWD 1 2010 FALLOFF TEST**  
**INFINITE CONDUCTIVITY FRACTURE TYPE CURVE MATCH**

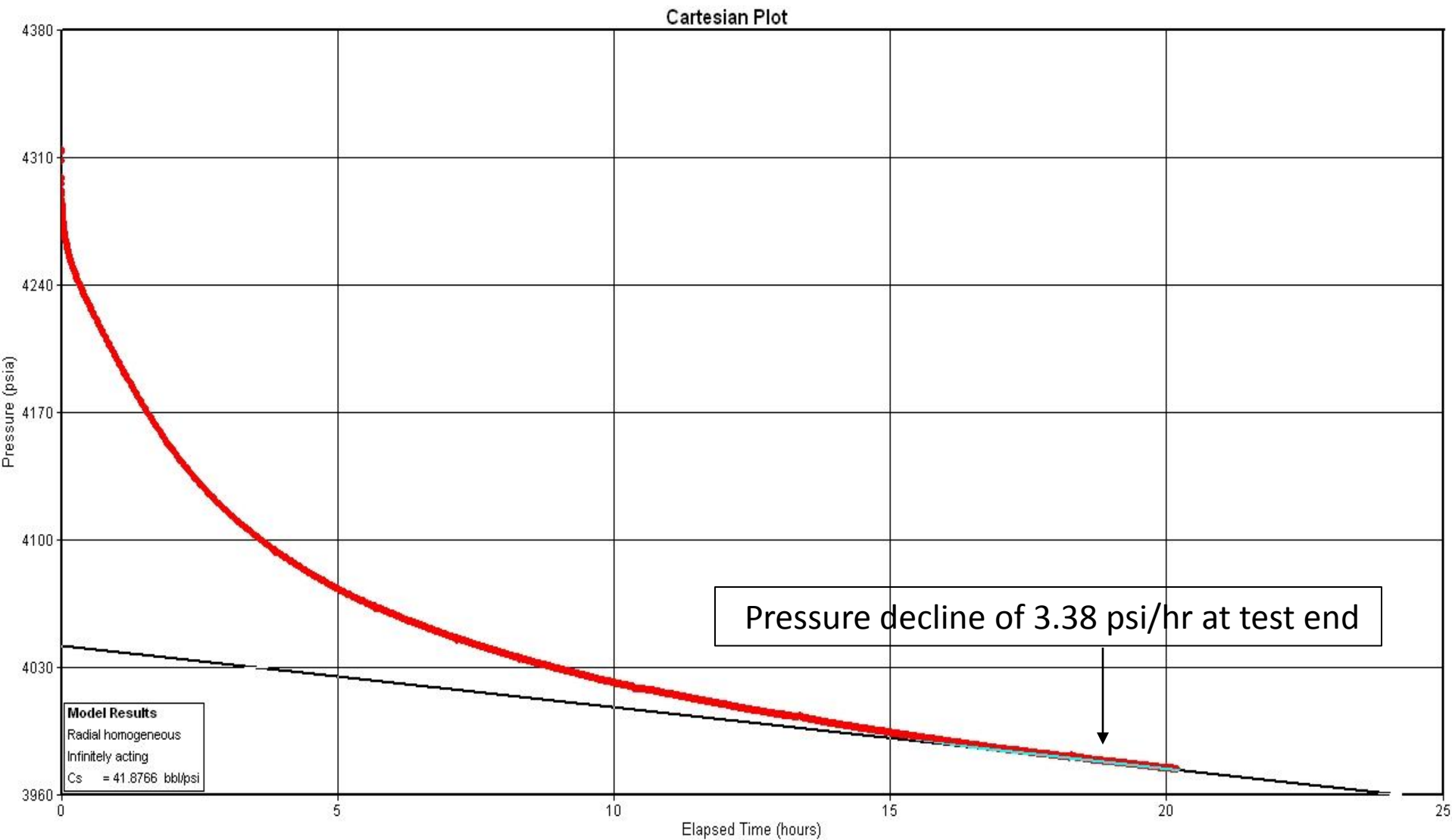




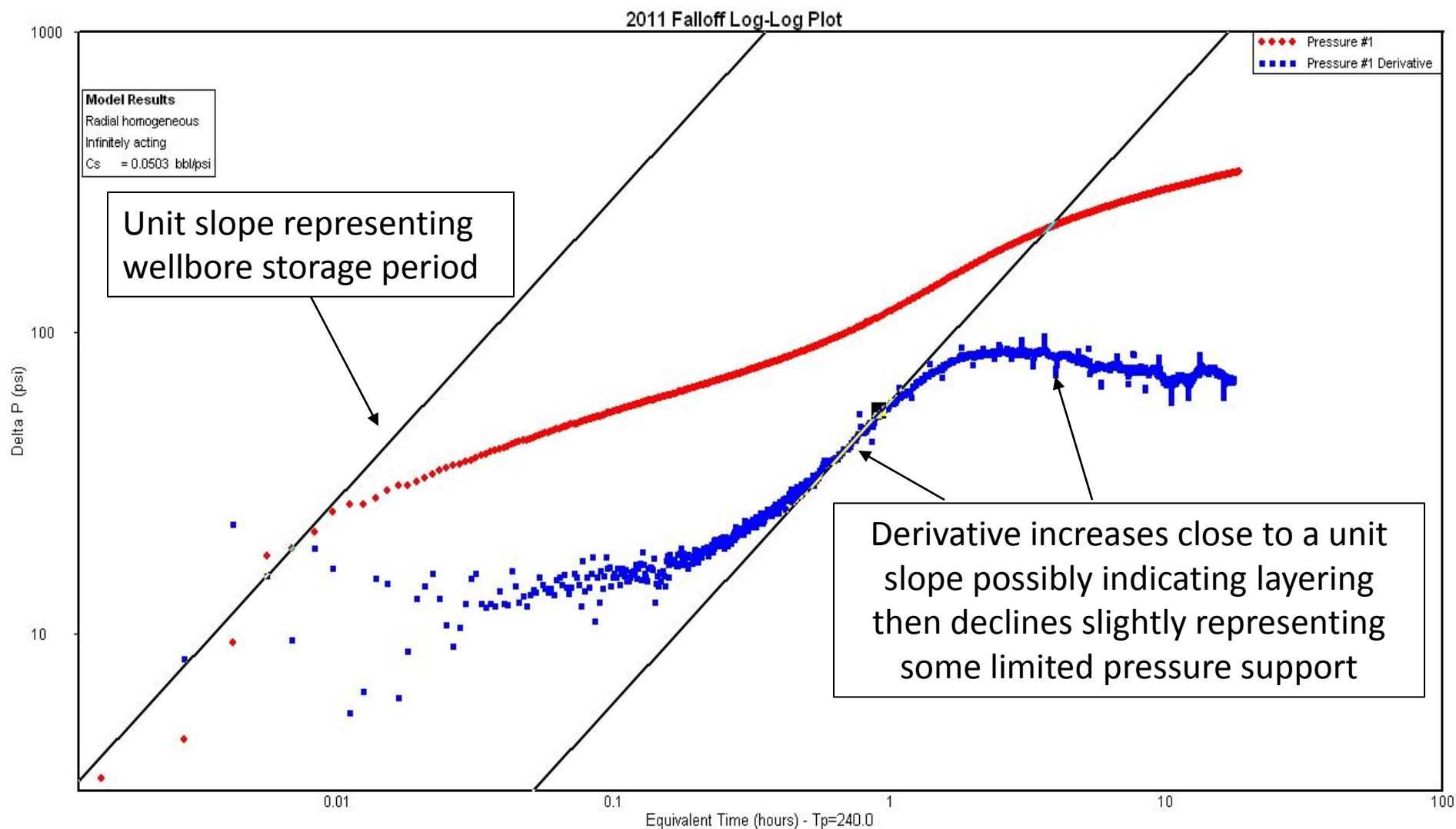
**FIGURE D-81: SPARKS DRIVE SWD 1 2010 FALLOFF TEST**  
**DUAL PERMEABILITY MODEL TYPE CURVE MATCH**



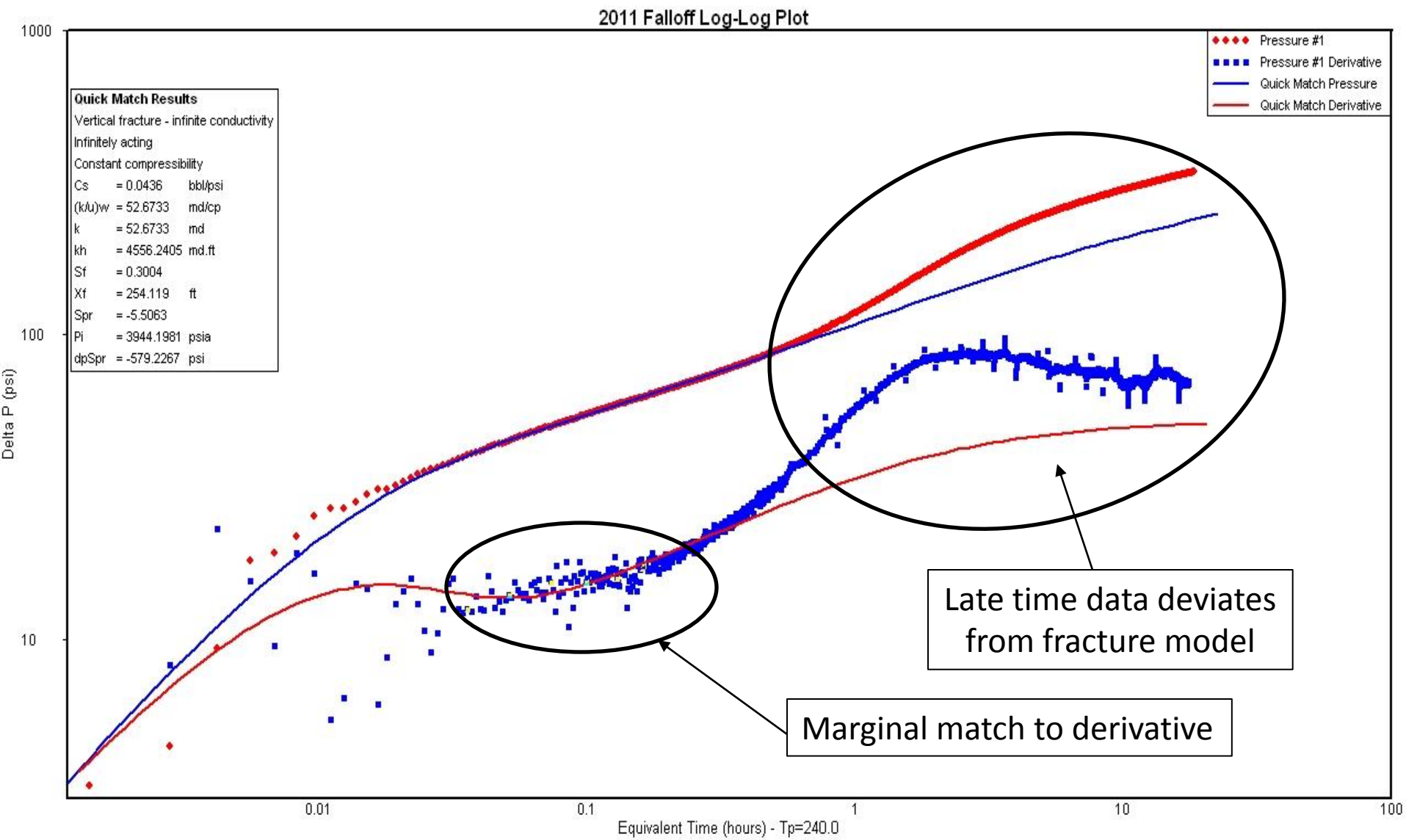
**FIGURE D-82: SPARKS DRIVE SWD 1 2011 FALLOFF TEST OVERVIEW PLOT**



**FIGURE D-83: SPARKS DRIVE SWD 2011 FALLOFF TEST LOG-LOG PLOT**



**FIGURE D-84: SPARKS DRIVE SWD 2011 FALLOFF TEST**  
**INFINITE CONDUCTIVITY TYPE CURVE MATCH**



## APPENDIX E: CENTRAL ARKANSAS AREA CASE STUDY

|  |      |
|--|------|
| Background .....   | E-1  |
| History of Seismicity.....   | E-1  |
| Geologic Setting .....   | E-2  |
| Oil and Gas Activity .....   | E-3  |
| Vicinity Disposal Wells .....  | E-3  |
| Data Collected .....   | E-4  |
| Data Reviewed .....  | E-4  |
| Operational Analysis Plots and Observations.....                     | E-5  |
| Pressure Transient Test Plots and Observations .....                 | E-7  |
| Wayne Edgmon 1 Step rate test (Figure E-38).....                     | E-7  |
| Actions taken by UIC regulatory agency in Central Arkansas area..... | E-9  |
| References .....   | E-10 |

### *BACKGROUND*

From 2009 through 2011 a series of minor earthquakes occurred near the towns of Guy and Greenbrier in Faulkner County, Arkansas. The news media initially attributed these quakes to hydraulic fracturing in the Fayetteville Shale unconventional gas play illustrate on (Figure E-1). Through deployment of additional seismographs, discussions with the various oil and gas operators, and coordination between the Arkansas Oil and Gas Commission (AOGC), Arkansas Geologic Survey (AGS) and Center for Earthquake Research and information (CERI) at the University of Memphis, a more detailed picture emerged.

### *HISTORY OF SEISMICITY*

In 1811 and 1812, a series of 7.7 earthquakes rocked the New Madrid Seismic Zone (NMSZ), (USGS, 2011a). In 1982, Arkansas experienced the Enola swarm of earthquakes with the largest magnitude of 4.7 (USGS, 2011b) as shown on the timeline in Figure E-2. The more recent Greenbrier area earthquakes were located nine miles from the edge of the Enola swarm and approximately 100 miles from the edge of the NMSZ as illustrated in Figure E-1. Additional seismometers, illustrated in Figure E-3, were deployed to investigate the Greenbrier area earthquakes. Detailed information about the Greenbrier area earthquakes is available from the publication by Steve Horton with CERI (Horton and Ausbrooks, 2011), and the AOGC 180A-2011-07 hearing Exhibits by Scott Ausbrooks with AGS (Ausbrooks, 2011a, 2011b, 2011c, 2011d) and Steve Horton (Horton, 2011).

A summary of the recent Greenbrier area earthquakes recorded in the ANSS, NEIC, and CERI catalogs, within a five mile radius of the case study wells discussed below, is provided in Table E-1 below and a timeline of events is shown on Figure E-4. A zoomed map area of the disposal

well and earthquake activity is included on Figure E-5. According to the AGS, both the Enola and Guy-Greenbrier focal mechanisms were N22°E (AGS, personal communication, September 15, 2011).

TABLE E-1: GREENBRIER AREA SEISMICITY THROUGH 1/31/2012

| Year | Starting Date | Number of Events | Magnitude |      |      | Ending Date |
|------|---------------|------------------|-----------|------|------|-------------|
|      |               |                  | Min.      | Avg. | Max. |             |
| 1982 | 1/18/1982     | 36               | 1.9       | 3.1  | 4.3  | 11/21/1982  |
| 1983 | 1/19/1983     | 9                | 1.8       | 2.5  | 3.5  | 7/12/1983   |
| 1984 | 7/12/1984     | 8                | 1.5       | 2.3  | 3.2  | 11/12/1984  |
| 1985 | 2/24/1985     | 24               | 1.3       | 2.1  | 3.3  | 12/24/1985  |
| 1986 | 1/5/1986      | 18               | 1.3       | 2.0  | 3.0  | 11/8/1986   |
| 1987 | 2/23/1987     | 10               | 1.2       | 2.1  | 2.9  | 12/20/1987  |
| 1988 | 1/2/1988      | 7                | 1.0       | 1.7  | 2.2  | 4/21/1988   |
| 1989 | 4/1/1989      | 3                | 1.5       | 1.9  | 2.2  | 4/6/1989    |
| 1990 | 8/17/1990     | 6                | 1.8       | 2.1  | 2.6  | 12/10/1990  |
|      |               |                  |           |      |      |             |
| 2001 | 5/4/2001      | 4                | 2.7       | 3.2  | 4.3  | 5/5/2001    |
| 2002 |               | 0                |           |      |      |             |
| 2003 | 12/14/2003    | 2                | 2.7       | 2.8  | 2.8  | 12/15/2003  |
| 2004 |               | 0                |           |      |      |             |
| 2005 | 1/27/2005     | 1                | 2.7       | 2.7  | 2.7  | 1/27/2005   |
| 2006 | 4/9/2006      | 2                | 2.8       | 2.8  | 2.8  | 10/17/2006  |
|      |               | 0                |           |      |      |             |
| 2009 | 10/15/2009    | 7                | 2.4       | 2.7  | 3.0  | 10/31/2009  |
| 2010 | 2/18/2010     | 677              | 0.2       | 1.8  | 4.4  | 12/31/2010  |
| 2011 | 1/1/2011      | 732              | 1.0       | 2.2  | 4.7  | 12/22/2011  |
| 2012 | 1/14/2012     | 2                | 2.0       | 2.1  | 2.2  | 1/14/2012   |

Five mile radial areas around each case study well along are shown in Figures E-8, E-10, E-12, and E-14. The corresponding seismicity timelines of events associated with each well are shown in Figures E-9, E-11, E-13, and E-15.

## GEOLOGIC SETTING

The Greenbrier area is located in the Arkansas valley region of the eastern Arkoma basin. There are at least three phases of faulting as shown on the East Arkoma Basin structural cross-section in Figure E-6. The most recent, normal listric faults sole out on the Mississippian-Pennsylvanian unconformity. The intra-Pennsylvanian normal faults, in some cases displace earlier basement

1 faults (Vanarsdale and Schweig, 1990). Not shown, is the recently discovered Guy-Greenbrier  
2 fault<sup>17</sup> that appears to be a fairly vertical, normal fault cutting from the basement up to the  
3 upper Pennsylvanian unconformity towards the north end (Horton and Ausbrooks, 2011;  
4 Chesapeake Energy, person communication, September 16, 2011).

5 The Paleozoic section contains alternating carbonates and shales overlying crystalline basement  
6 rock below the Arbuckle. As illustrated in the stratigraphic column in Figure E-7, the confining  
7 zones separating the Boone and Hunton formations are thin or missing in the study area. The  
8 lower confining unit separating the Arbuckle from the Cambrian St. Francis Aquifer group and  
9 basement is also missing in this area.

#### 10 *OIL AND GAS ACTIVITY*

11 The central portion of the Fayetteville Shale gas play started in 2004 and covers parts of  
12 Cleburne, Conway, Faulkner, Independence, Pope, Van Buren and White counties. Fayetteville  
13 shale production wells are typically horizontally completed with laterals from 4,000' to 7000' in  
14 length at depths between 2,000' and 6,000'.

#### 15 *VICINITY DISPOSAL WELLS*

16 For the reservoir engineering analysis of this case study, EPA focused on four area disposal  
17 wells: E.W. Moore Estate 1-22, Wayne L. Edgmon 1, Trammel 7-13 1-8D, and SRE 8-12 1-17  
18 SWD. Data was gathered from the permit applications and operational history for each well.  
19 Table E-2 provides a summary of each well's construction and completion information. Figures  
20 E-16 through E-18 are wellbore schematics of the Moore, Edgmon, and Trammel wells. No  
21 wellbore schematic was included for the SRE well. Additional details for each well are  
22 summarized below:

23 *E W Moore Estate 1-22 SWD*: Permit No. 39487; Commercial well; Maximum permitted  
24 pressure of 3,000 psig and rate of 6,000 BPD; Total Depth: 10,600'; Initial injection Jun 1, 2009;  
25 Final injection: Jul 15, 2011; Authorized injection zone 7,760'-10,600'; Injection formations -  
26 Boone through Arbuckle; plugged and abandoned Sep 29, 2011.

27 *Wayne L Edgmon (1) SWD*: Permit No. 36380 Commercial well; Maximum permitted pressure  
28 of 8454 psig and rate of 20,000 BPD; Total Depth: 12,163'; Authorized initial Injection Aug 18,  
29 2010; Final injection Mar 14, 2011; Authorized formation - Arbuckle; temporarily abandoned.  
30 This well was originally drilled as an exploratory well into Precambrian crystalline basement.

---

<sup>17</sup> Note that the precise location and upper elevation depend on the particular velocity model used, and vary between the two sources of information.

*Trammel 7-13 1-8D SWD*: Permit No. 41079; Maximum permitted pressure of 2300 psig and rate of 12,000 BPD; Total depth: 7,160'; Authorized initial injection April 2009; Final injection June 2011; Authorized injection zone 6,503'-6,590'; Injection formation - Boone; plugged and abandoned Oct 19, 2011.

*SRE 8-12 1-17 SWD*: Permit No. 43266; Maximum permitted pressure of 3330 psig and rate of 20,000 BPD; Total Depth: 6,500'; Initial injection Jul 8, 2010; Final injection Mar 2011; Authorized injection zone 5,992'-6,277'; Injection formations - Boone and Hunton; plugged and abandoned Sep 30, 2011.

TABLE E-2: GREENBRIER AREA WELL CONSTRUCTION INFORMATION SUMMARY

| Well                   | Total Depth | Casing Diameter and Seat | Tubing Diameter and Seat | Completed Interval   |
|------------------------|-------------|--------------------------|--------------------------|----------------------|
| E.W. Moore Estate 1-22 | 10600'      | 5 ½" to 8087'            | 2 7/8" to 8077'          | Openhole below 8087' |
| Wayne Edgmon 1         | 12163'      | 4 ½" to 12162'           | 2 7/8" to 7710'          | 7806'-10970'         |
| Trammel 7-13 1-8D      | 7160'       | 5 ½" to 7126'            | 3 ½" to 6800'            | 6836'-6936'          |
| SRE 8-12 1-17 SWD      | 6500'       | 7" to 6500'              | 4 ½" to 5925'            | 5975'-6460'          |

#### DATA COLLECTED

Data for these four wells were collected from AOGC via their website and from the state regulatory hearing documentation associated with the disposal well moratorium ruling. Permitting documents provided details concerning completion depths, construction information, and permit conditions. Operational monitoring reports provided several months of injection rates and wellhead pressures with data being recorded as often as every hour in some wells.

#### DATA REVIEWED

Data were divided into two areas: operational and pressure transient testing. All four wells had operational data for analysis. A step rate test was available for the Edgmon. Transient testing data consisted of surface pressure falloff tests embedded in the monitored pressure data for the Edgmon, SRE, and Trammel wells. Injection rates fluctuated significantly in all three wells preceding the falloffs. The pressures were recorded at the surface so no useful pressures were available after a well went on a vacuum during a shut-in period, making the falloff pressure responses of limited duration.

Operational data consisted of monthly, bi-hourly, and hourly wellhead pressures and injection volumes. The high data recording rate yielded fairly noisy data sets for operational analysis, with Edgmon data being especially noisy, but the added frequency provided sufficient data for a limited falloff test analysis during some of the shut-in periods.



Surface pressures were converted to approximate bottomhole pressures (BHP) at the tubing seat depth of each well. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A brine specific gravity of 1.025 was used based on permitting documentation for the SRE well.

#### *OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS*

The operational rate and pressure data overview plot for the four case study wells is included in Figures E-19 through E-22. Pressure gradient plots (Figures E-23 through E-26), Hall integral and derivative plots (Figures E-27 through E-31), Silin slope plots (Figures E-32 through E-34) were also prepared and are discussed below.

Table E-3 summarizes the assumed reservoir pressure value used for each Hall plot and comparison with the average pressure value determined from the corresponding slope plot.

**TABLE E-3: COMPARISON OF ASSUMED HALL PLOT AVERAGE PRESSURE VALUES AND SLOPE PLOT - DETERMINED AVERAGE RESERVOIR PRESSURES**

| Well                   | Hall Plot Assumed Pressure<br>(psia) | Slope Plot-Determined Pressures<br>(psia) |
|------------------------|--------------------------------------|---|
| E.W. Moore Estate 1-22 | 3500                                 | 6258                                      |
| Trammel 7-13 1-8D      | 3800                                 | 4216                                      |
| SRE 8-12 1-17 SWD      | 2400                                 | 3504                                      |

The Arkansas case study had a large number of low to moderate level earthquake events recorded, making it possible to plot a well established cumulative event trend. To determine if the earthquake cumulative event trend followed the Hall integral trend, tandem plots of cumulative earthquake events and Hall integral response versus cumulative water injection were prepared for the Moore, SRE, and Trammel wells and are shown in Figures E-35 through E-37. The Edgmon operating data was intermittent, resulting in an unstable Hall integral trend and excluded from this report.

The operating pressure data analysis completed for each well is summarized below. The results of the tandem plots are also included. Because of the location of the well from the Guy-Greenbrier fault, a tandem plot was not prepared for the E.W. Moore Estate 1-22 disposal well.

The operating pressure data analysis completed for each well is summarized below:

- Operational data overview plots (Figures E-19 through E-22)
  - E.W. Moore Estate 1-22 (Figure E-19)

- Pressures did not fluctuate with rate changes
- Wayne Edgmon 1 (Figure E-20)
  - Operated intermittently with significant rate fluctuations
  - Falloff test recorded during final well shut-in from more frequent surface pressure measurements during enhanced monitoring
- Trammel 7-13 1-8D (Figure E-21)
  - Rates dipped between January and June 2010 with limited pressure decline
- SRE 8-12 1-17 (Figure E-22)
  - Operated intermittently with significant rate fluctuations
  - Short falloff test during final well shut-in
    - Well went on vacuum so surface pressure data no longer useful for falloff test analysis
- Operating pressure gradient plots (Figures E-23 through E-26)
  - Rule of thumb pressure gradient was not used because of higher fracture gradient determined for this area
  - Highest operating gradients in the Moore well (Figure E-23)
- Hall integral and derivative plot (Figures E-27 through E-30)
  - E.W. Moore Estate 1-22 (Figure E-27)
    - Zoomed plot showed a subtle negative slope break during its first 50,000 bbls of injection (Figure E-28)
      - Derivative trend generally below Hall integral with some scatter
  - Wayne Edgmon 1
    - No Hall plot generated - small diameter tubing size coupled with intermittent disposal data resulting in an unstable Hall integral trend
  - Trammel 7-13 1-8D (Figure E-29)
    - Hall integral by itself shows both positive and negative slope changes
    - Hall derivative noisy
  - SRE 8-12 1-17 SWD (Figure E-30)
    - Normal injection behavior except for two early slope breaks
    - Zoomed Hall plot (Figure E-31) showed negative slope breaks at approximately 440,000 (8/28/2010) and 900,000 (10/6/2010) cumulative bbls
- Silin slope plot (Figures E-32 through E-34)
  - E.W. Moore Estate 1-22 (Figure E-32)
  - Wayne Edgmon 1
    - No slope plot due intermittent disposal data
  - Trammel 7-13 1-8D (Figure E-33)

- SRE 8-12 1-17 SWD (Figure E-34)
- Tandem plot: (Figures E-35 through E-37)
  - E.W. Moore Estate 1-22 (Figure E-35)
  - Wayne Edgmon 1
    - No tandem plot
  - Trammel 7-13 1-8D (Figure E-36)
  - SRE 8-12 1-17 SWD (Figure E-37)

## *PRESSURE TRANSIENT TEST PLOTS AND OBSERVATIONS*

### WAYNE EDMON 1 STEP RATE TEST (FIGURE E-38)

The WG reviewed the step rate test conducted in the Edgmon and found conflict between the reported data and field notes as summarized in Tables E-4 and E-5. The data from the recorded data and field notes in Table E-5 were used for preparation of the linear plot. A drastically reduced pressure response occurred during rate step 6. The small diameter tubing size in the well coupled with high injection rate values resulted in the calculated bottomhole pressures dropping below the actual measured surface pressures due to severe calculated friction loss as shown in Figure E-38. No slope breaks were observed in the surface pressure data. The test was not considered suitable for quantitative analysis.

TABLE E-4: CLARITA OPERATING WAYNE L. EDMON STEP RATE TEST (4/10/10).\*

| Step | Injection Rate (BPM) | Injection Rate (BWPD) | Surface Injection Pressure (psig) | Frictional Pressure (psig) | Estimated Hydrostatic Pressure (psig) | Estimated BHP Pressure (psig) |
|------|----------------------|-----------------------|-----------------------------------|----------------------------|---------------------------------------|-------------------------------|
| 1    | 5.9                  | 8500                  | 760                               | 710                        | 3465                                  | 3515                          |
| 2    | 7.0                  | 10100                 | 1204                              | 1134                       | 3465                                  | 3535                          |
| 3    | 8.4                  | 12100                 | 1704                              | 1584                       | 3465                                  | 3585                          |
| 4    | 9.9                  | 14200                 | 2380                              | 2125                       | 3465                                  | 3695                          |
| 5    | 11.2                 | 16100                 | 3015                              | 2715                       | 3465                                  | 3765                          |
| 6    | 14.4                 | 20800                 | 4960                              | 4360                       | 3465                                  | 4065                          |
| 7    | 17.4                 | 25000                 | 6882                              | 6097                       | 3465                                  | 4250                          |

\* Edgmon data summary table in report listed inconsistent time increments and injection rates compared to the data from the recording instruments and field notes included in the report. Time increments = 15 minutes; water weight = 8.55 ppg; water specific gravity = 1.025; depth to top perforation = 7806 feet.

TABLE E-5: CLARITA OPERATING WAYNE L. EDGMON STEP RATE TEST (4/10/10).\*

| Step | Rate from data (bpm) | Rate (gpm) | Surface Pressure (psig) | Bottomhole Pressure (psig) | Friction Pressure (psi) | Bottomhole Pressure Corrected for Friction (psig) | Time Increments (min) |
|------|----------------------|------------|-------------------------|----------------------------|-------------------------|---|-----------------------|
| 1    | 5.8                  | 243.6      | 760                     | 4182                       | 1200                    | 2982  | 60                    |
| 2    | 6.9                  | 289.8      | 1204                    | 4626                       | 1655                    | 2971  | 60                    |
| 3    | 8.3                  | 348.6      | 1675                    | 5097                       | 2329                    | 2768  | 60                    |
| 4    | 9.9                  | 415.8      | 2380                    | 5802                       | 2337                    | 2575  | 60                    |
| 5    | 11.1                 | 466.2      | 3015                    | 6437                       | 3988                    | 2449  | 60                    |
| 6    | 11.2                 | 470.4      | 1090                    | 4512                       | 4055                    | 457   | 60                    |
| 7    | 14.8                 | 621.6      | 4997                    | 8419                       | 6791                    | 1628  | 180                   |

\* Edgmon summary table compiled from recorded data and field notes. Pressure dropped during rate step 6; report provided no explanation for pressure decrease.

Surface pressure falloff test data were also reviewed for the Edgmon, Trammel and SRE, and Trammel wells using PanSystem® welltest analysis software. The final falloff periods were analyzed and the reservoir characteristics are illustrated in Figures E-39 through E-43 for the three disposal wells located closest to the Guy-Greenbrier fault. The pressure transient analysis of the step rate test for the Edgmon and the final falloff tests for each of the three wells are summarized below:

- Wayne Edgmon 1 Step rate test (Figure E-38)
  - Linear plot of surface pressure test data converted to bottomhole
    - Anomalous behavior observed during step 6
      - At a constant injection rate of 11.2 bpm
      - Surface injection pressure fluctuated greatly
        - Start at approximately 2860 psi for 5 min
        - Drop abruptly to approximately 960 psi
        - Climb gradually to approximately 1090 psi
    - Calculated BHPs declined with increasing injection rates (friction factor of 150)
      - Friction factor of 140 resulted in a negative bottomhole pressure for the final rate step so used 150
- Wayne Edgmon 1 Final falloff
  - Log-log plot analyzed using an equivalent time function (Figure E-39)
    - Time function accounts for rate history
    - Response was dominated by wellbore storage
      - Pressure derivative response exceeded the pressure change
      - Test using an equivalent time function was deemed unanalyzable
- Trammel 7-13 1-8D Final falloff test (Figures E-40 and E-41)
  - Overview plot of shut-in periods and final falloff (Figure E-40)

- Log-log plot indicated a fracture or highly stimulated completion signature (Figure E-41)
  - Completely dominated by linear flow
  - Could not be type curve matched
- SRE 8-12 1-17 final falloff test (Figures E-42 and E-43)
  - Overview plot of shut-in periods and final falloff (Figure E-42)
  - Log-log plot indicated a fracture or highly stimulated completion signature
    - Matched using an infinite conductivity fracture model (Figure E-43)
    - Indicated a long fracture half length (> 500 feet) for this well's completion
    - Late test time derivative response indicated some pressure support present

#### *ACTIONS TAKEN BY UIC REGULATORY AGENCY IN CENTRAL ARKANSAS AREA*

Initial response was deployment of additional seismometers to better record the actual event epicenters (surface location) and focus location (depth). This was done through the combined efforts of Arkansas Geological Survey (AGS) and University of Memphis Center for Earthquake Research and Information (CERI), with some of the monitor stations directly linked into the USGS National Earthquake Information Center.

Following initial identification of the Guy-Greenbrier fault, the Arkansas Oil and Gas Commission (AOGC) established a moratorium on the drilling of any new Class II disposal wells in an area surrounding and in the immediate vicinity of the seismic activity in December 2010; and required the operators of the seven existing Class II disposal wells operating in the moratorium area to provide bi-hourly injection rates and pressures for a period of 6 months, thru July 2011. During the moratorium period AGS and CERI analyzed the injection data and seismic activity to determine if there was a relationship. The injection-induced seismicity project considered the five deeper wells closest to the Guy-Greenbrier fault selecting the three wells closest to the fault for further analysis.

Using (Wells and Coopersmith, 1994) equations, from the estimated fault rupture length and area, the potential maximum (moment) magnitude it could produce was estimated to be between 5.6 and 6.0. (Horton, 2011)

In February 2011, following a series of larger magnitude earthquakes, (4.7 with damage reported), the operators of the three disposal wells nearest the seismic activity voluntarily agreed to shut-in the subject disposal wells prior to the issuance of an AOGC cessation order. AOGC issued a cessation order on March 4, 2011 requiring the subject wells to cease disposal operations. In July 2011, following the conclusion of the moratorium study, AOGC established a revised permanent moratorium area in which no further Class II disposal wells could be drilled

1 and that four of the original seven disposals wells included in the original moratorium area  
2 were required to be plugged. The revised moratorium area was based on the trend of the fault  
3 identified as the cause of the seismic activity. The operators of three of the wells (SRE,  
4 Trammel and Edgmon) voluntarily agreed to plug the subject disposal wells. The operator of  
5 the fourth disposal well (Moore) was ordered to do so following the July 2011 Commission  
6 Hearing. Three of the disposal wells (SRE, Trammel, and Moore) have been plugged by the  
7 operators, as of the date of this report. (Note: the operator of the Edgmon disposal well is in  
8 bankruptcy and the well will probably be plugged by the Commission in spring 2012 under the  
9 Commission Abandoned and Orphaned Well Plugging Program).

10 AOGC finalized amendments to their Class II disposal well rules effective in February 2012.  
11 These additional requirements, dealing with seismic issues, only affected disposal wells in the  
12 Fayetteville Shale development area. In addition AOGC is studying the feasibility of establishing  
13 a permanent seismic array in the Fayetteville Shale development area to monitor future  
14 disposal well operations, thereby creating a potential “early warning” system to developing  
15 seismic activity and possibly allowing sufficient time to develop adequate management  
16 strategies.

#### 17 REFERENCES

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19 Ausbrooks, S. M., 2011a, Exhibit 23: Geologic overview of north-central Arkansas and the Enola  
20 and Guy-Greenbrier earthquake swarm areas, 2011, *in* Arkansas Oil and Gas Commission  
21 public hearing on Class II commercial disposal well or Class II disposal well moratorium,  
22 Order No. 180A-2-2011-07, El Dorado, Arkansas.

23 Ausbrooks, S. M., 2011b Exhibit 24: Overview of the E. W. Moore Estate No. 1 well (Deep Six  
24 SWD) and small aperture seismic array, 2011, *in* Arkansas Oil and Gas Commission public  
25 hearing on Class II commercial disposal well or Class II disposal well moratorium, Order  
26 No. 180A-2-2011-07, El Dorado, Arkansas.

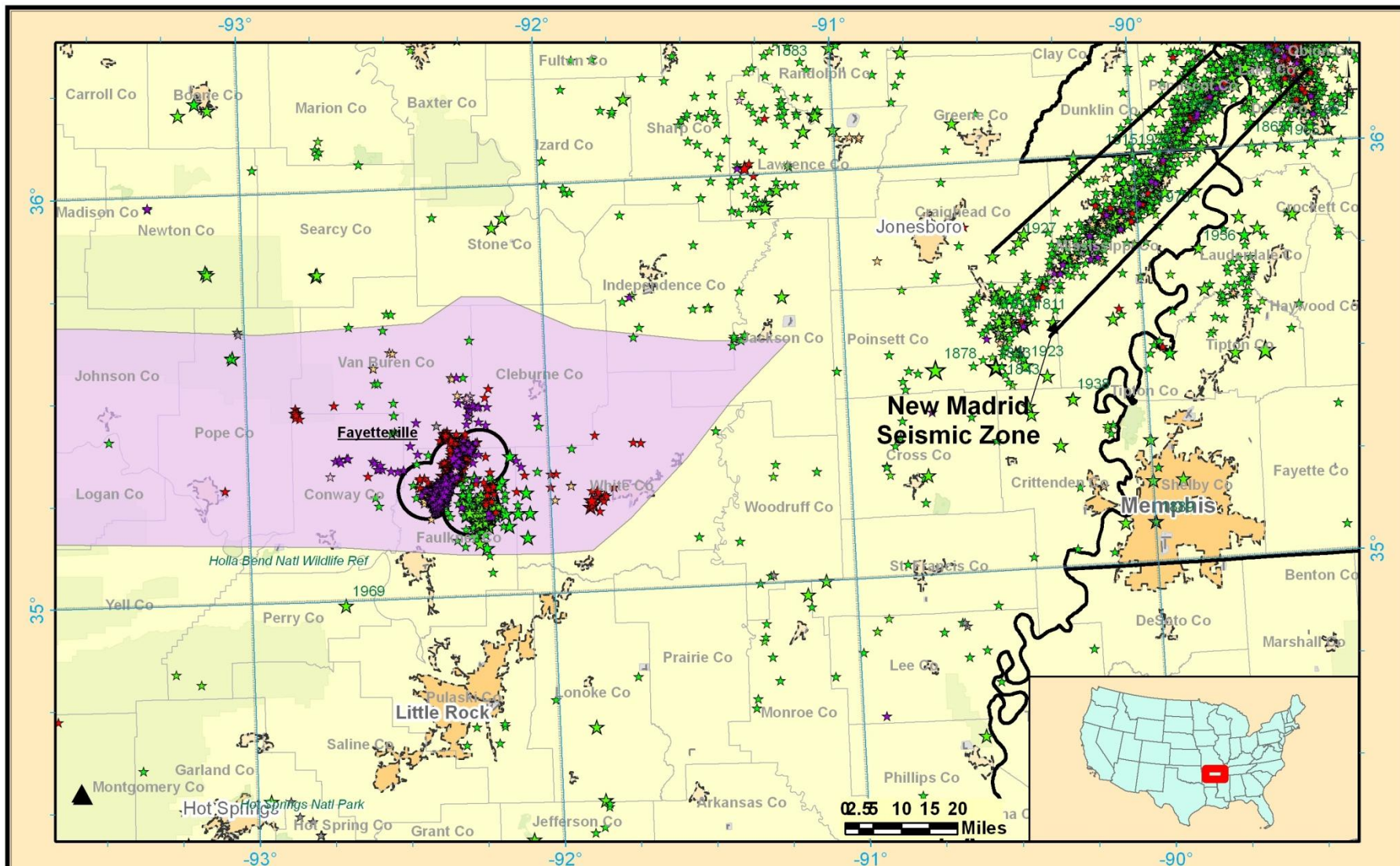
27 Ausbrooks, S. M., 2011c, Exhibit 25: Clarita Operating, LLC, Wayne Edgmon SWD data, 2011, *in*  
28 Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well or  
29 Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

30 Ausbrooks, S. M., 2011d, Exhibit 30: Docket 063-2008-01, initial Deep Six permit hearing, 2011,  
31 *in* Arkansas Oil and Gas Commission public hearing on Class II commercial disposal well  
32 or Class II disposal well moratorium, Order No. 180A-2-2011-07, El Dorado, Arkansas.

33 Horton, S., 2011, Exhibit 22: Central Arkansas earthquake activity: Draft of testimony to  
34 Arkansas Oil and Gas Commission, *in* Arkansas Oil and Gas Commission public hearing  
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36 180A-2-2011-07, El Dorado, Arkansas.

- 1 Horton, S., and Ausbrooks, S., 2011, Earthquakes in central Arkansas triggered by fluid injection  
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3 Seismicity Potential in Energy Technologies: Dallas, Texas.
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- 5 USGS, 2011a, New Madrid 1811-1812 earthquakes, US Geological Survey, Accessed November  
6 22 <<http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php>>, Last  
7 updated May 24, 2011.
- 8 USGS, 2011b, Poster of the 2010-2011 Arkansas Earthquake Swarm, US Geological Survey,  
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- 10 Vanarsdale, R. B., and Schweig, E. S., 1990, Subsurface structure of the eastern Arkoma Basin:  
11 AAPG Bulletin, v. 74, p. 1030-1037.
- 12 Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude,  
13 rupture length, rupture width, rupture area, and surface displacement: Bulletin of the  
14 Seismological Society of America, v. 84, no. 4, p. 974-1002.

# FIGURE E-1: CENTRAL ARKANSAS AREA SEISMICITY



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

## Magnitude

- No Magnitude
- ★ 0 - 3
- ★ 3.1 - 5
- ★ 5.1 - 6

## Earthquake Year

- |      |       |
|------|-------|
| 2012 | 2009  |
| 2011 | 2008  |
| 2010 | <2008 |

## Seismometers

- △ <all other values>
- △ Ended
- ▲ Operating

## Albers Projection

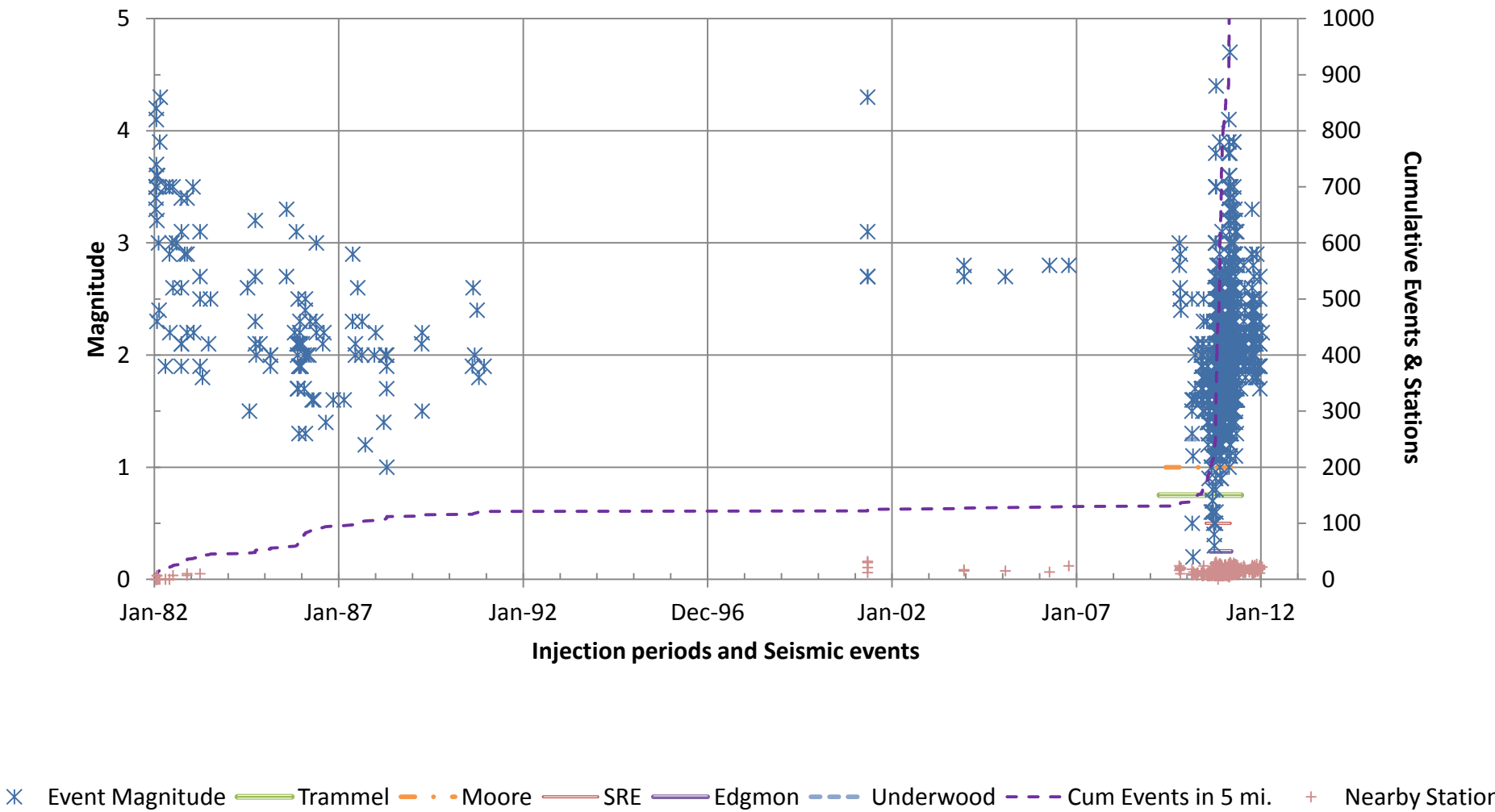
Central Meridian: -96  
1st Std Parallel: 20  
2nd Std Parallel: 60  
Latitude of Origin: 40

Compiled by:  
Nancy Dorsey, EPA R6



FIGURE E-2: TIMELINE OF CENTRAL ARKANSAS SEISMICITY

Guy-Greenbrier Seismicity



**FIGURE E-3: TEMPORARY SEISMOMETER STATIONS & EVENTS DEFINING THE GUY-GREENBRIER FAULT**

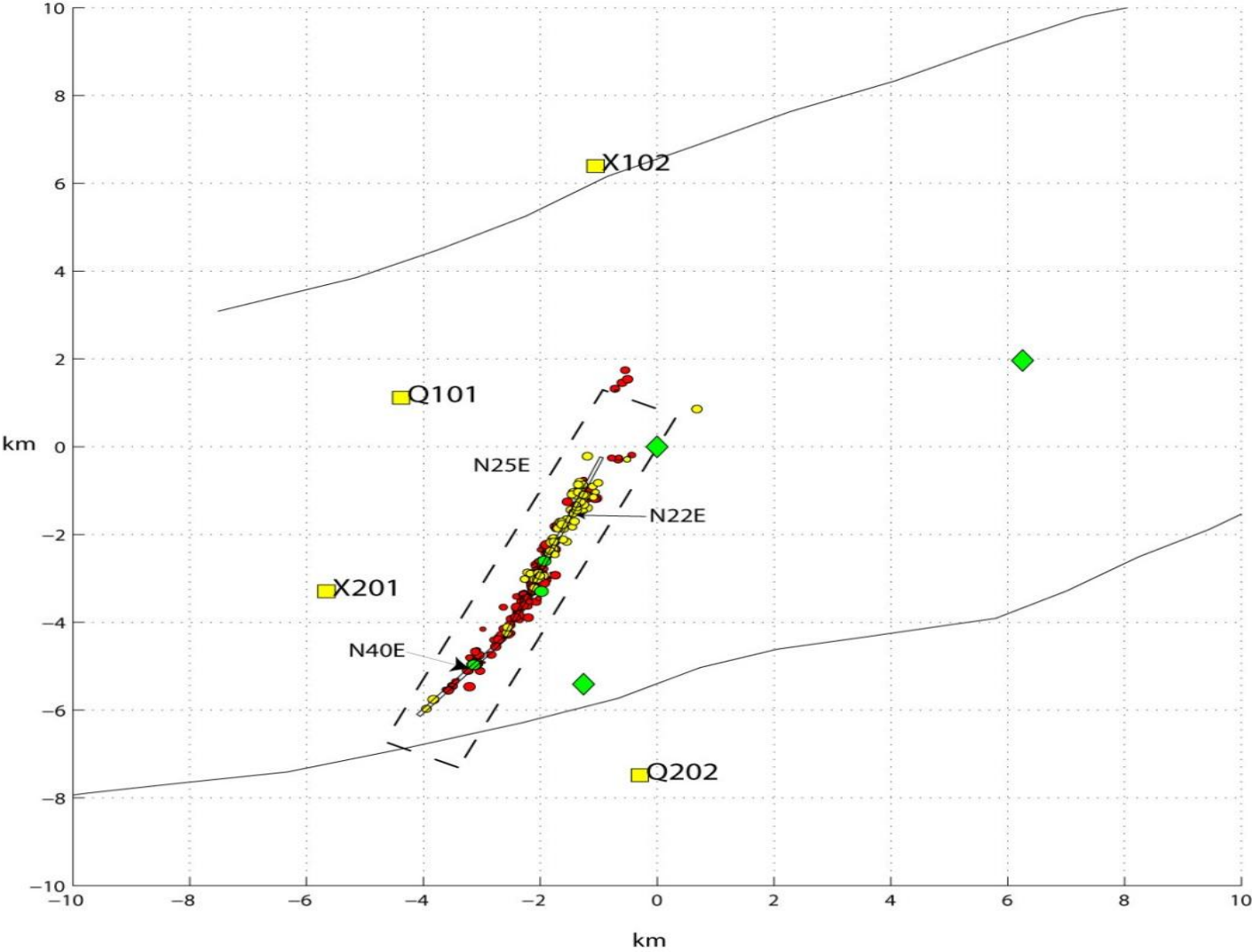
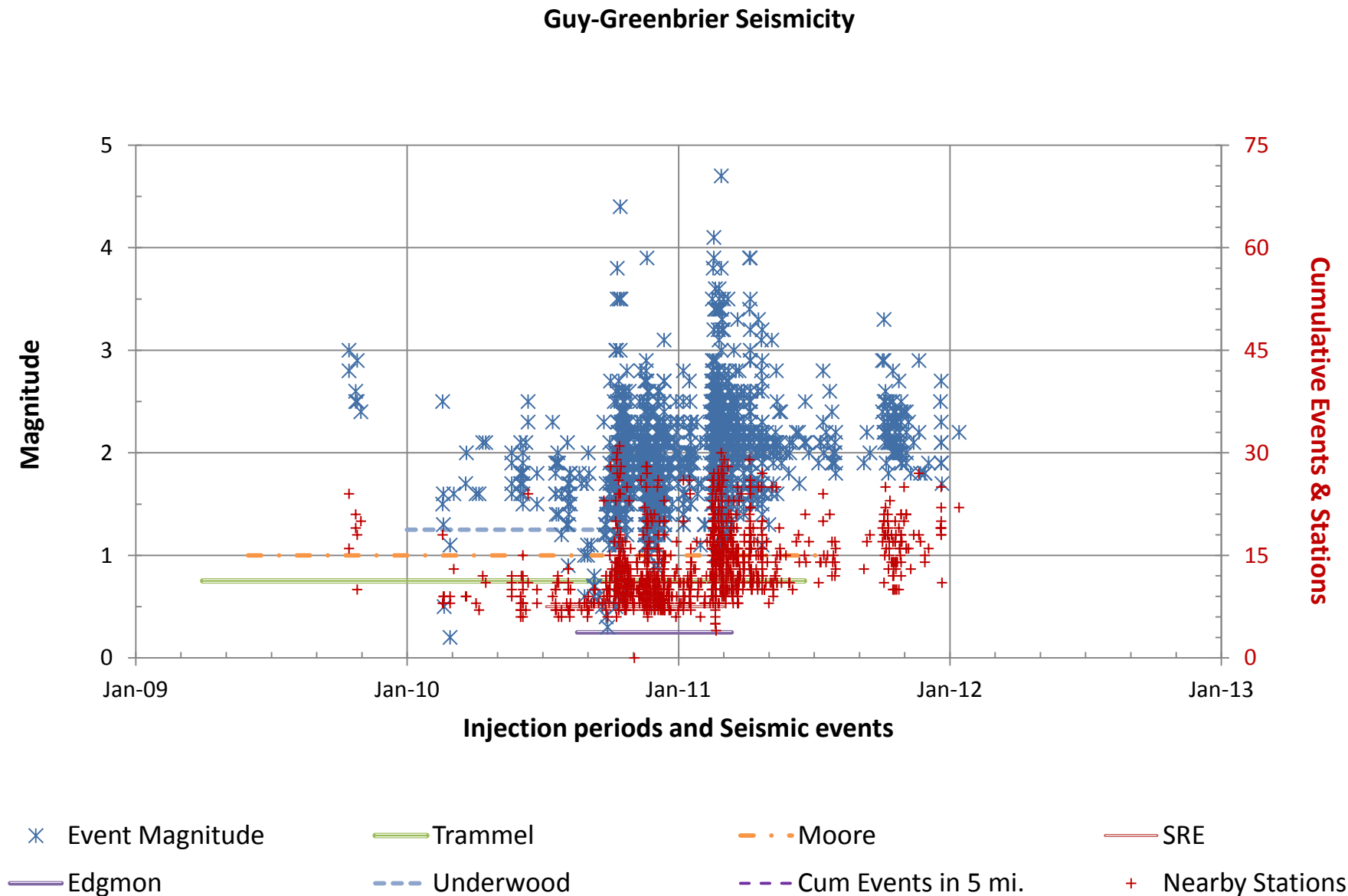
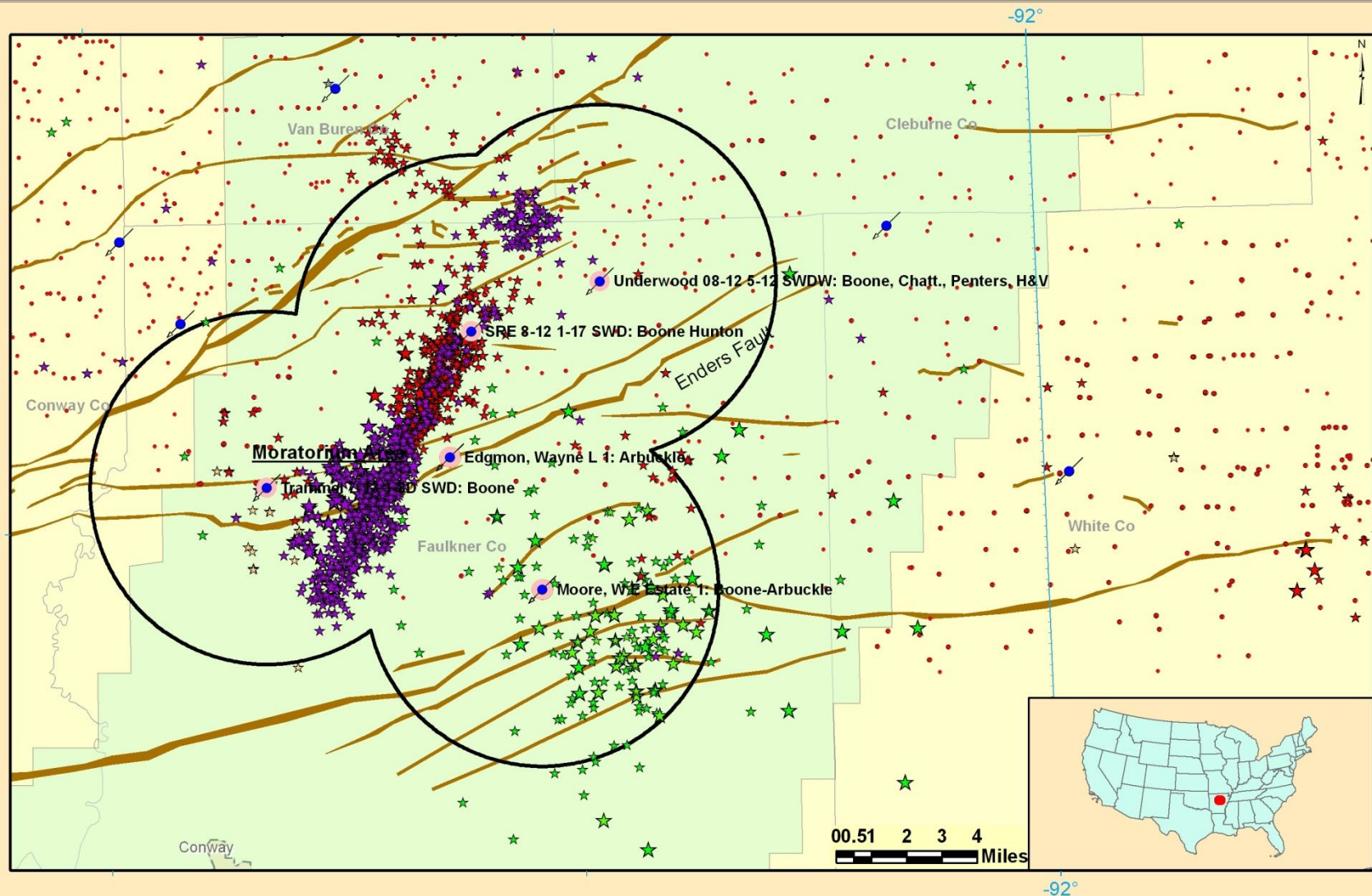


FIGURE E-4: RECENT TIMELINE OF CENTRAL ARKANSAS SEISMICITY



# FIGURE E-5: MAP OF DISPOSAL WELLS AND EARTHQUAKE ACTIVITY



Earthquakes through 01/31/2012

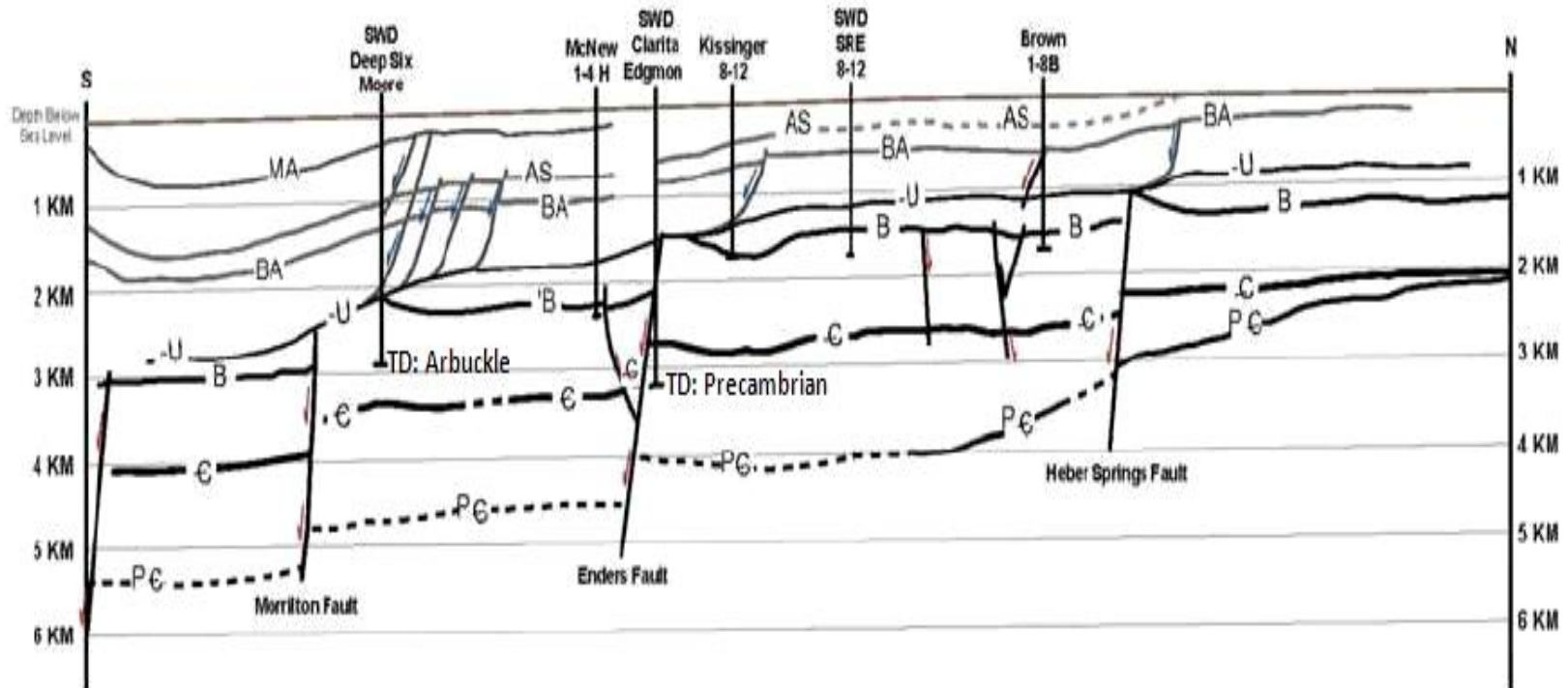
If legend item, does not show in map, it is not in the area.

| Magnitude      | Earthquake Year | Seismometers         | Wells                     | Horizon                |
|----------------|-----------------|----------------------|---------------------------|------------------------|
| • No Magnitude | 2012            | △ <all other values> | ● Injection/Disposal Well | — Structure Contours   |
| ★ 0 - 3        | 2009            | △ Ended              | ● Gas Well                | — Faults: Fayetteville |
| ★ 3.1 - 5      | 2011            | ▲ Operating          | ● Oil Well                | ○ Search area          |
| ★ 5.1 - 6      | 2010            | ● Wells of Interest  | ○ Commercial Inj          |                        |
|                | <2008           |                      |                           |                        |

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

**FIGURE E-6: EAST ARKOMA BASIN STRUCTURAL CROSS-SECTION  
(with permission from author)**



MA: basal Atoka SS BA: basal Atoka SS unc: Mississippian-Pennsylvanian unconformity B: Boone Fm C: Cambrian reflector P: Precambrian reflector

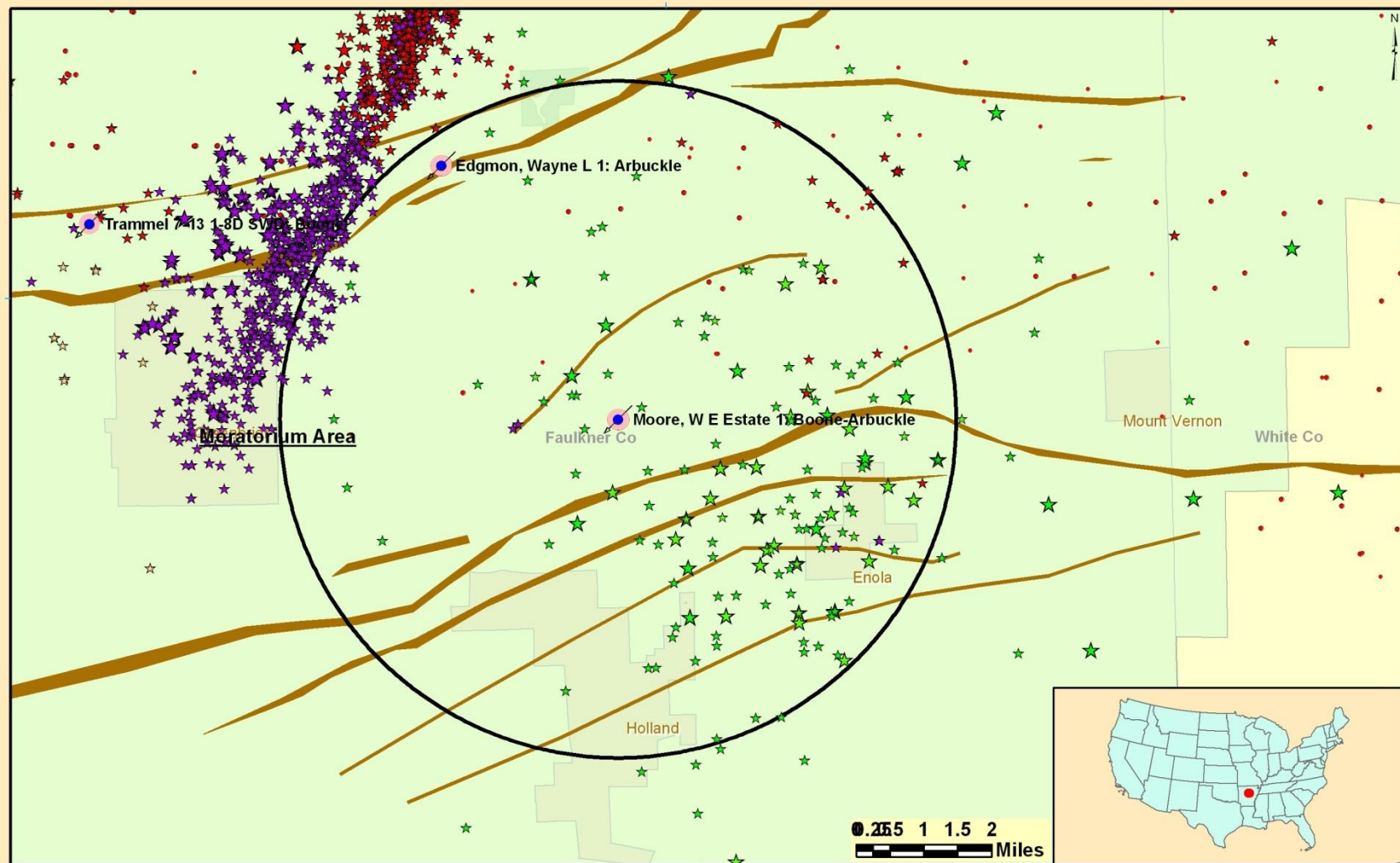
From Ausbrooks Exhibit 23 based on Vanarsdale and Schweig, Subsurface Structure of the Eastern Arkoma Basin, AAPG Bulletin, V. 74, N. 7, p. 1030-1037, 1990.

FIGURE E-7: STRATIGRAPHIC COLUMN

| AGE               | ROCK UNITS                       | REFLECTORS |
|-------------------|----------------------------------|------------|
| Pennsylvanian     | Atoka Fm                         | MA         |
|                   |                                  | LA         |
|                   |                                  | BA         |
|                   | Morrowan Section                 | M          |
|                   |                                  | U          |
| Mississippian     | Pitkin Ls                        | B          |
|                   | Fayetteville Sh                  |            |
|                   | Ls & Sh                          |            |
|                   | Boone Fm                         |            |
| Cambrian-Devonian | Hunton                           | C          |
|                   | Arbuckle                         |            |
|                   |                                  |            |
| Pre-Cambrian      | Cambrian Dolomite & granite wash | Pc         |
|                   | Granitic Basement                |            |



**FIGURE E-8: 5 MILE RADIUS OF THE MOORE ESTATE NO. 1-22 SWD**



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**

• No Magnitude  
★ 0 - 3  
★ 3.1 - 5  
★ 5.1 - 6

**Earthquake Year**

2012 2009  
2011 2008  
2010 <2008

**Seismometers**

△ <all other values>  
△ Ended  
▲ Operating  
● Wells of Interest

**Wells**

● Injection/Disposal Well  
● Gas Well  
● Oil Well  
● Commercial Inj

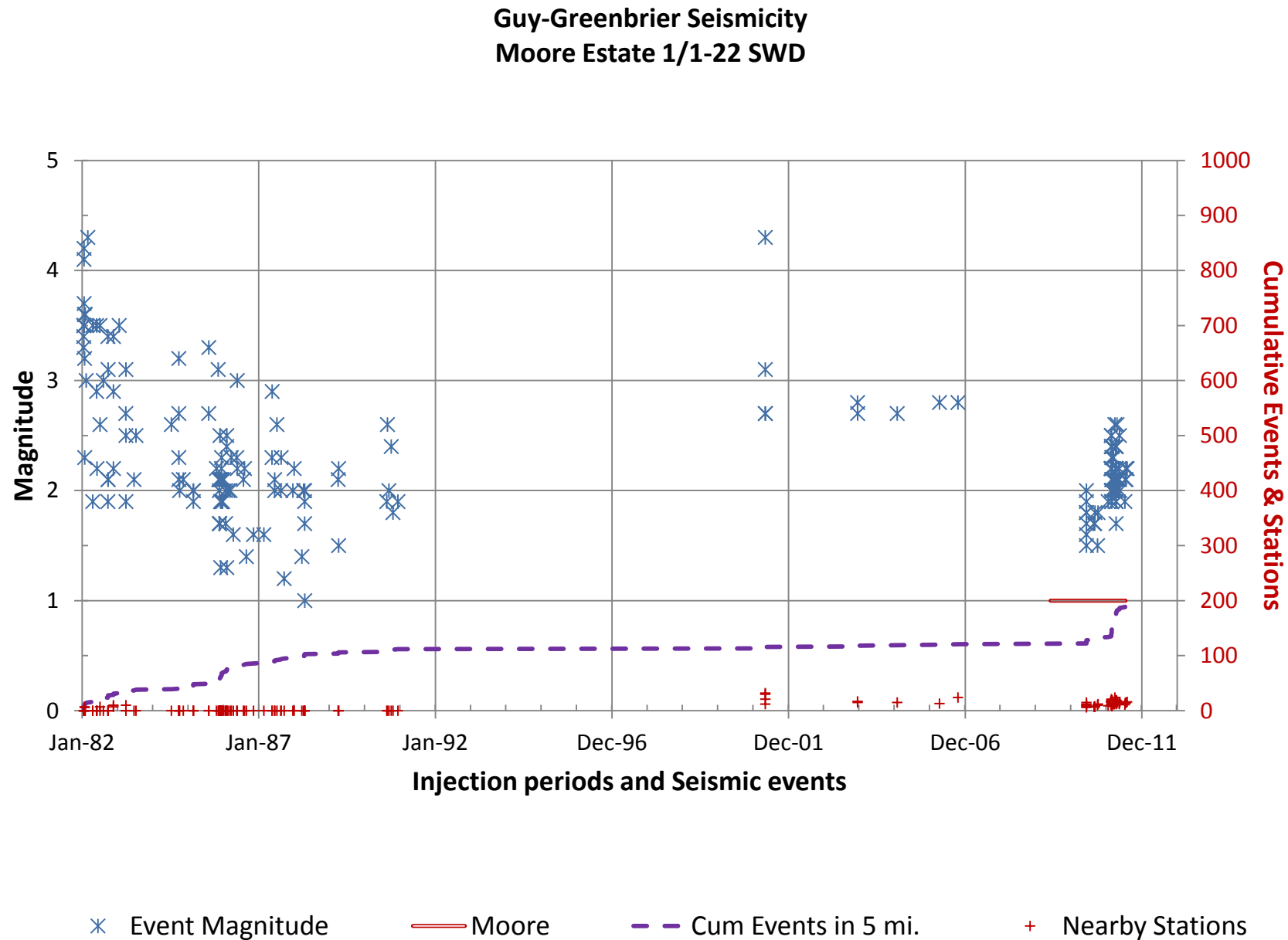
**Horizon**

— Structure Contours  
— Faults: Fayetteville  
○ Search area

**Albers Projection**  
Central Meridian: -96  
1st Std Parallel: 20  
2nd Std Parallel: 60  
Latitude of Origin: 40

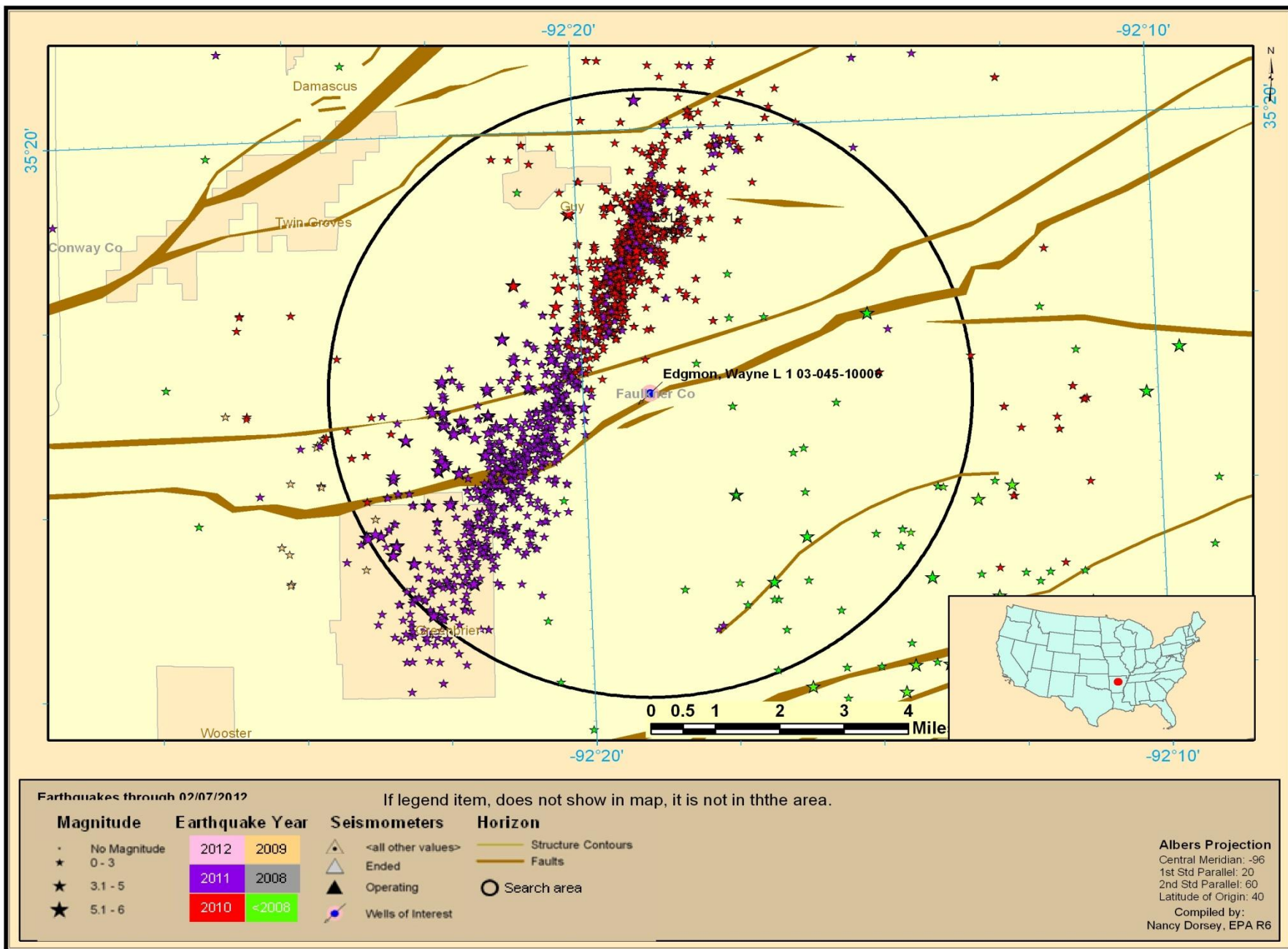
Compiled by:  
Nancy Dorsey, EPA R6

**FIGURE E-9: SEISMICITY TIMELINE FOR MOORE ESTATE NO. 1-22 SWD**

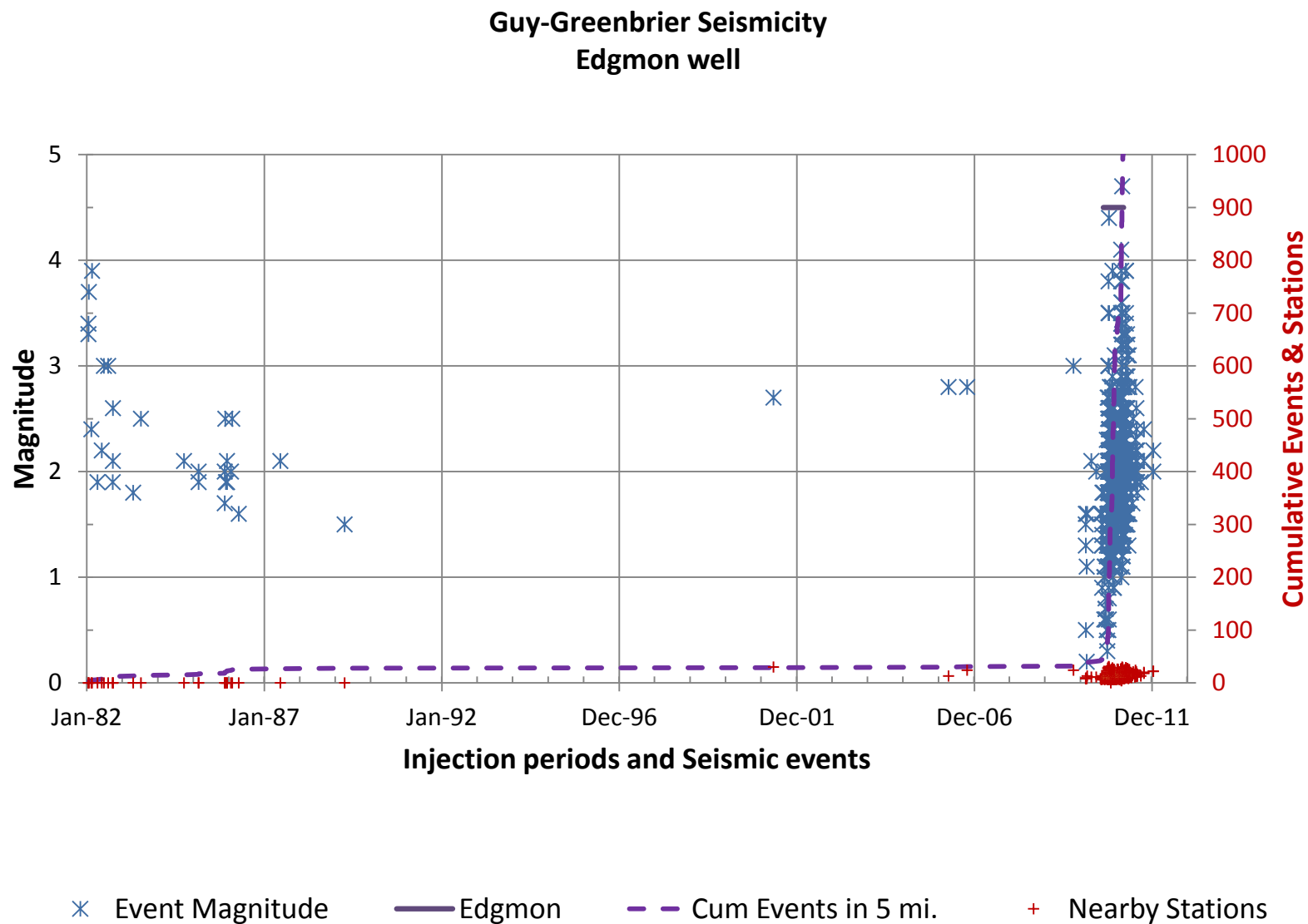




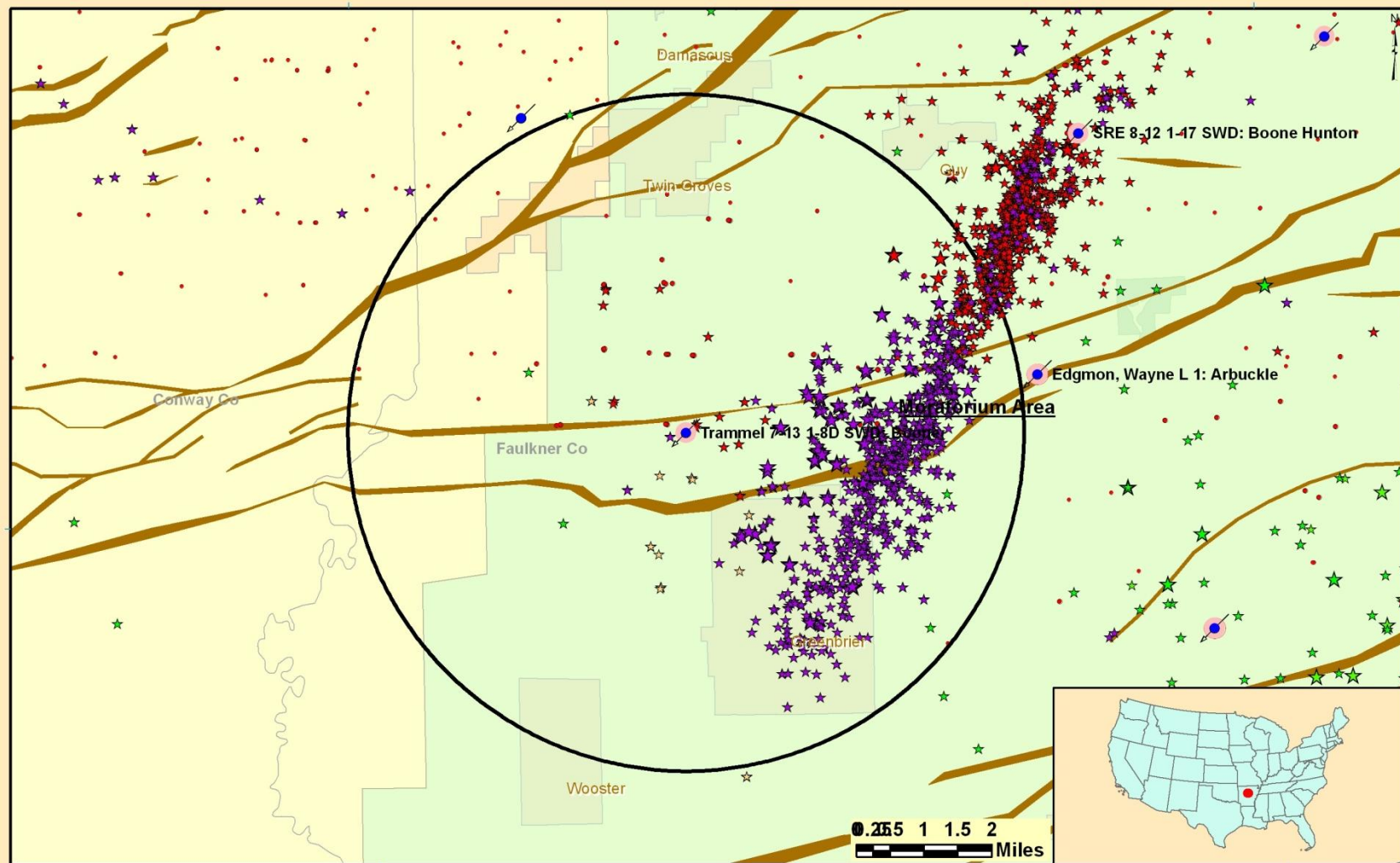
**FIGURE E-10: 5 MILE RADIUS OF THE EDGMON NO. 1**



**FIGURE E-11: SEISMICITY TIMELINE FOR EDGMON NO. 1**



# FIGURE E-12: 5 MILE RADIUS FROM THE TRAMMEL 7-13 1-8D SWD



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**

• No Magnitude  
 ★ 0 - 3  
 ★ 3.1 - 5  
 ★ 5.1 - 6

**Earthquake Year**

2012 2009  
 2011 2008  
 2010 <2008

**Seismometers**

△ <all other values>  
 △ Ended  
 ▲ Operating  
 ● Wells of Interest

**Wells**

● Injection/Disposal Well  
 ● Gas Well  
 ● Oil Well  
 ● Commercial Inj

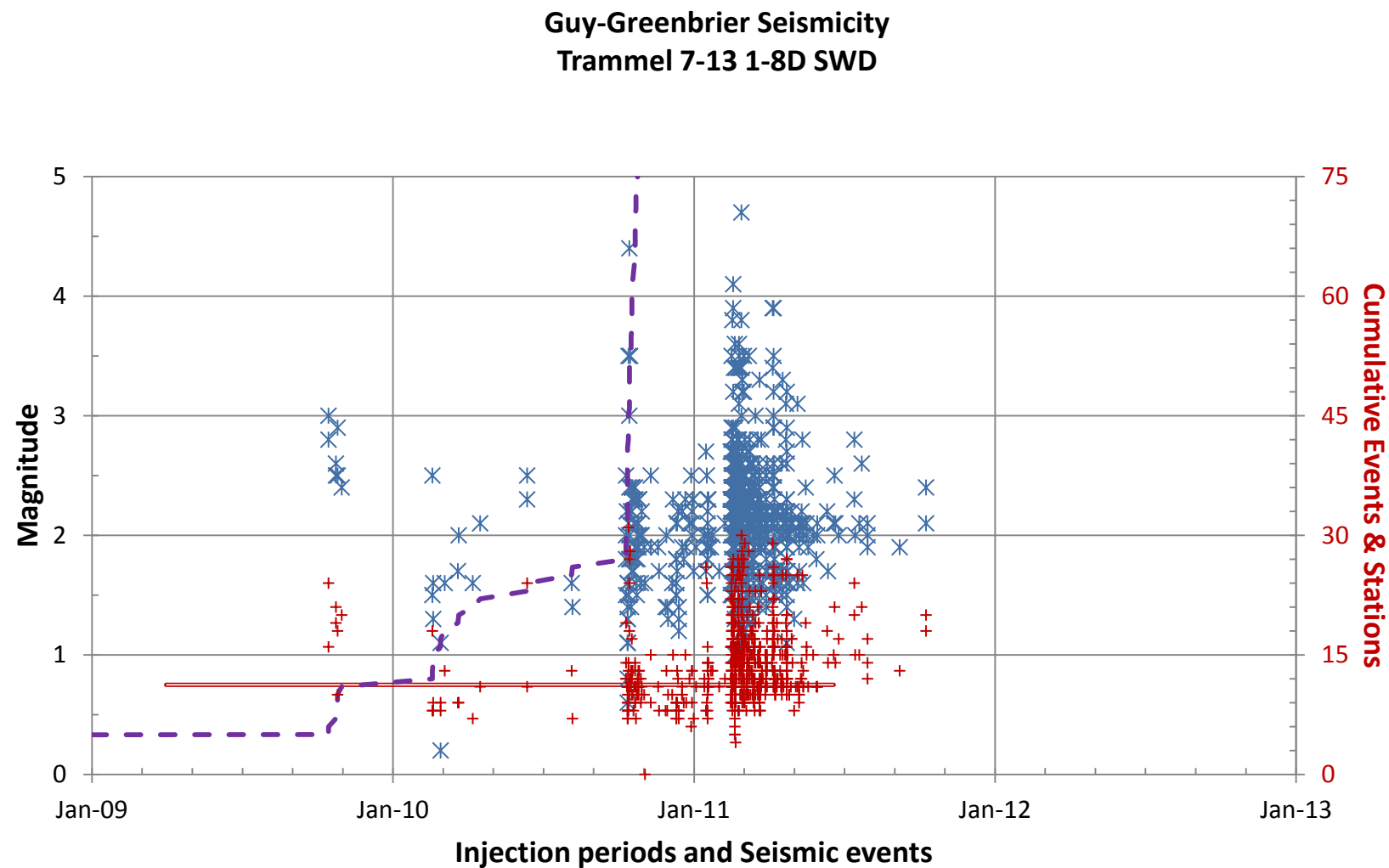
**Horizon**

— Structure Contours  
 — Faults: Fayetteville  
 ○ Search area

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

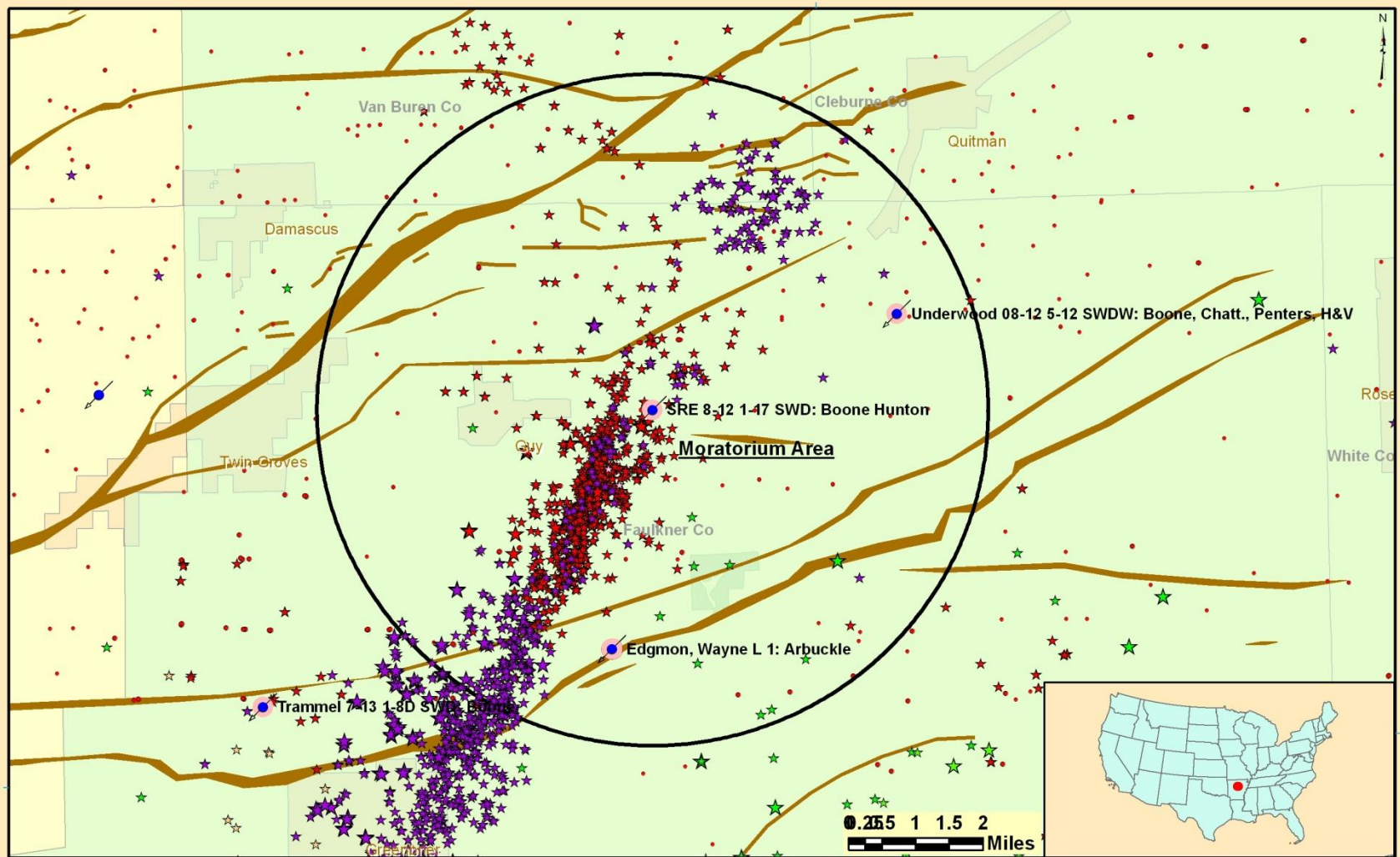
**FIGURE E-13: SEISMICITY TIMELINE FOR TRAMMEL 7-13 1-8D SWD**



× Event Magnitude      — Trammel      - - Cum Events in 5 mi.      + Nearby Stations



**FIGURE E-14: 5 MILE RADIUS FROM THE SRE 8-12 1-17 SWD**



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**  
 \* No Magnitude  
 ★ 0 - 3  
 ★ 3.1 - 5  
 ★ 5.1 - 6

**Earthquake Year**  
 2012  
 2011  
 2010  
 2009  
 2008  
 <2008

**Seismometers**  
 ▲ <all other values>  
 ▲ Ended  
 ▲ Operating  
 ● Wells of Interest

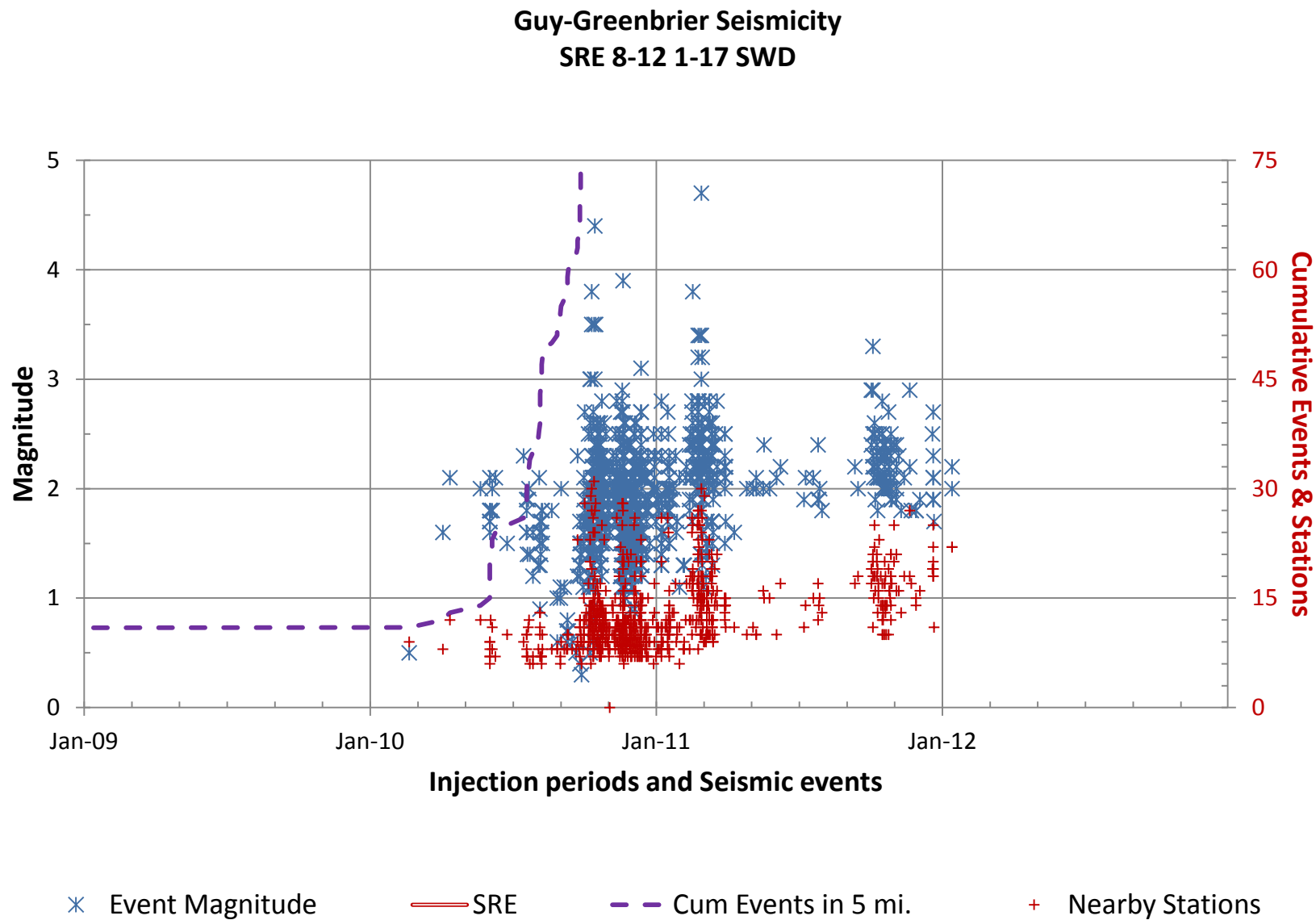
**Wells**  
 ● Injection/Disposal Well  
 ● Gas Well  
 ● Oil Well  
 ● Commercial Inj

**Horizon**  
 — Structure Contours  
 — Faults: Fayetteville  
 ○ Search area

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

**FIGURE E-15: SEISMICITY TIMELINE FOR SRE 8-12 1-17 SWD**



# FIGURE E-16: E W MOORE ESTATE 1-22 SWD WELLBORE SCHEMATIC

PLAT 314 WATER DIST. COR. SECTION, SEC.  
E W Moore Estate 1-22 SWDW Wellbore Diagram  
Faulkner County, Arkansas

current 11/15/2007

Well Name E W Moore Estate 1-22  
Location SE SW Sec 22-T7N R12W API # 03 045-10002  
660' FSL & 1980' FWL

Loc Except # NA  
Spacing Order # NA  
Formations

Date Spud 3/26/2007 re-entry  
Drilling Finished 10/4/2007 re-entry  
Date Completed  
TD 10600 Logs Run  
CBL Yes  
TOC 6790  
GL 295 KB 313

## Casing & Cementing

Conductor  
Surface 13 3/8" 523  
Intermediate 10-3/4" 45 9 & 49 sppf 2604 550 sx  
Production 5-1/2" 17 8087 634 sx (sqzdz)

## Completion

Formations Arbuckle 7750-10600

## Equipment in Hole

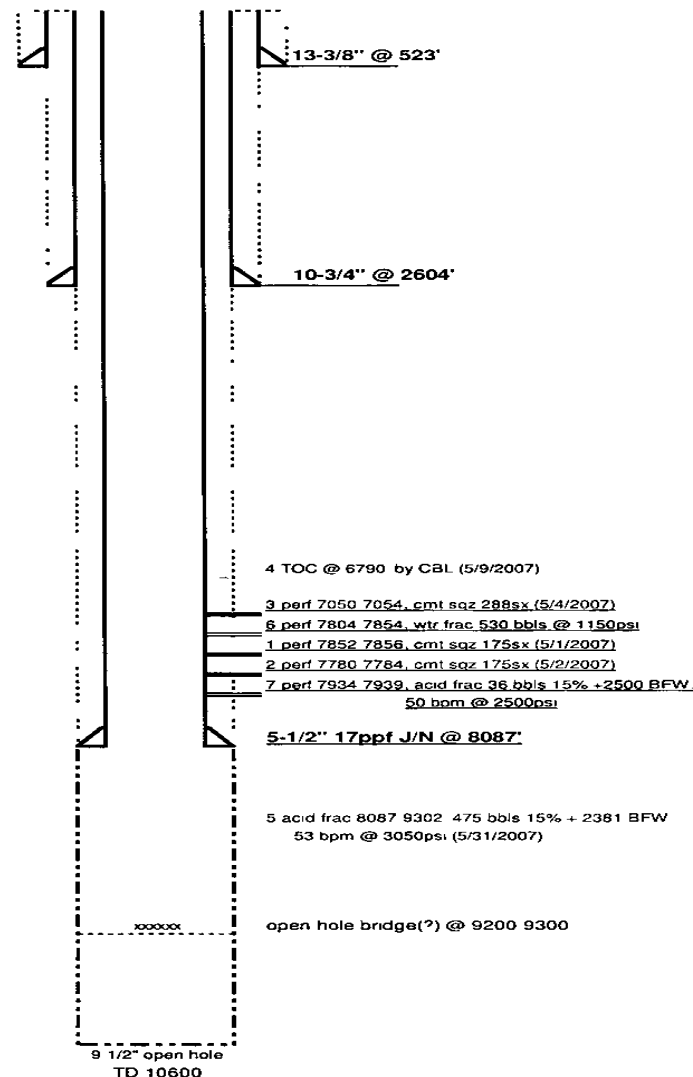
tbg 2-7/8" 6 sppf none  
packer none  
tailpipe none

## Equipment on Surface

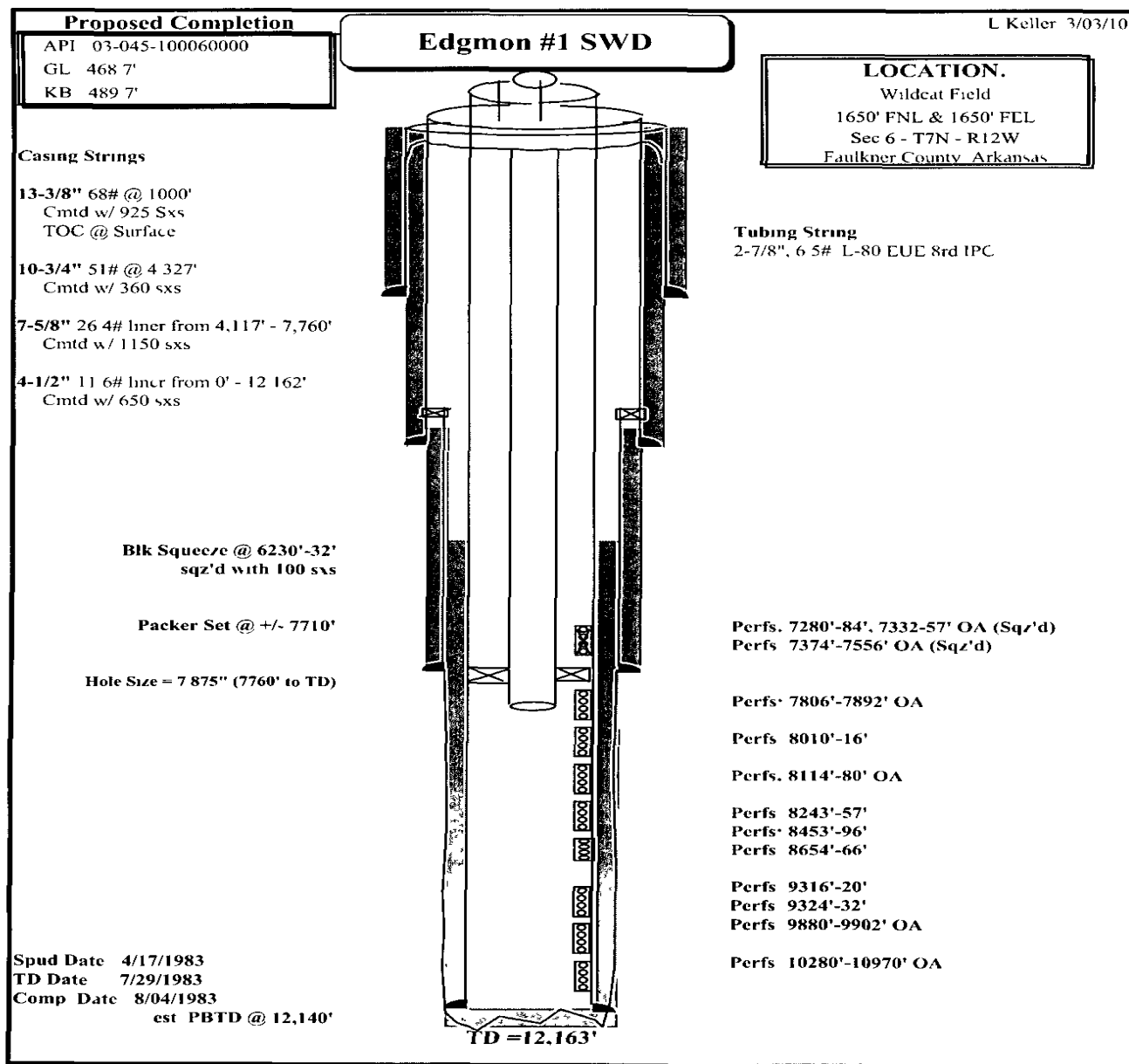
Casinghead C22 - 10-3/4" SOW x 11" 3m w/ 2" LPO  
Tubinghead TCM - 11" 3m X 7 1/16" 5m w/ (2) 2 1/16" 5m FE wing valves  
Tree B2P 7-1/16" 5m x 2-9/16" Adapter (coated) w/ (2) 2 9/16" 5m master valves (SS)  
& (1) 2-9/16" 5m wing valve & 2-9/16" x 2-9/16" 5m studded tee w/ BHTA

## History

## Comments



# FIGURE E-17: WAYNE L EDGMON NO. 1 SWD WELLBORE SCHEMATIC





## FIGURE E-18: TRAMMEL 7-13 1-8D SWD WELLBORE SCHEMATIC

WELL : Trammel 7-13 1-8D SWD      PROPERTY # 621044  
LOCATION : Sec. 8-7N-13W      (LEGALS)  
COUNTY : Faulkner      STATE: Arkansas  
ELEVATION : GL: 480' (15' AGL)      KB: 495'  
DATE : 12/17/08      PREPARED BY: M. Bale

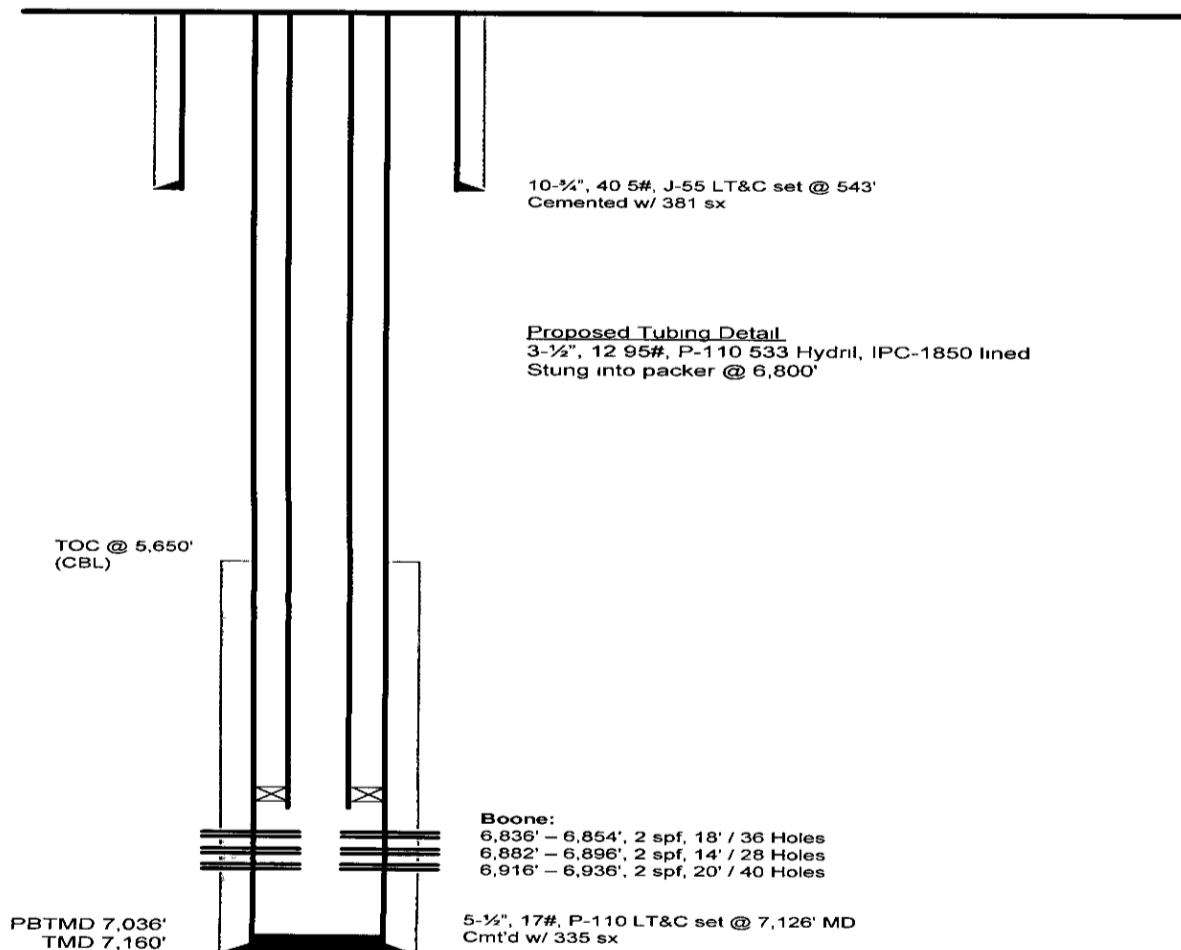
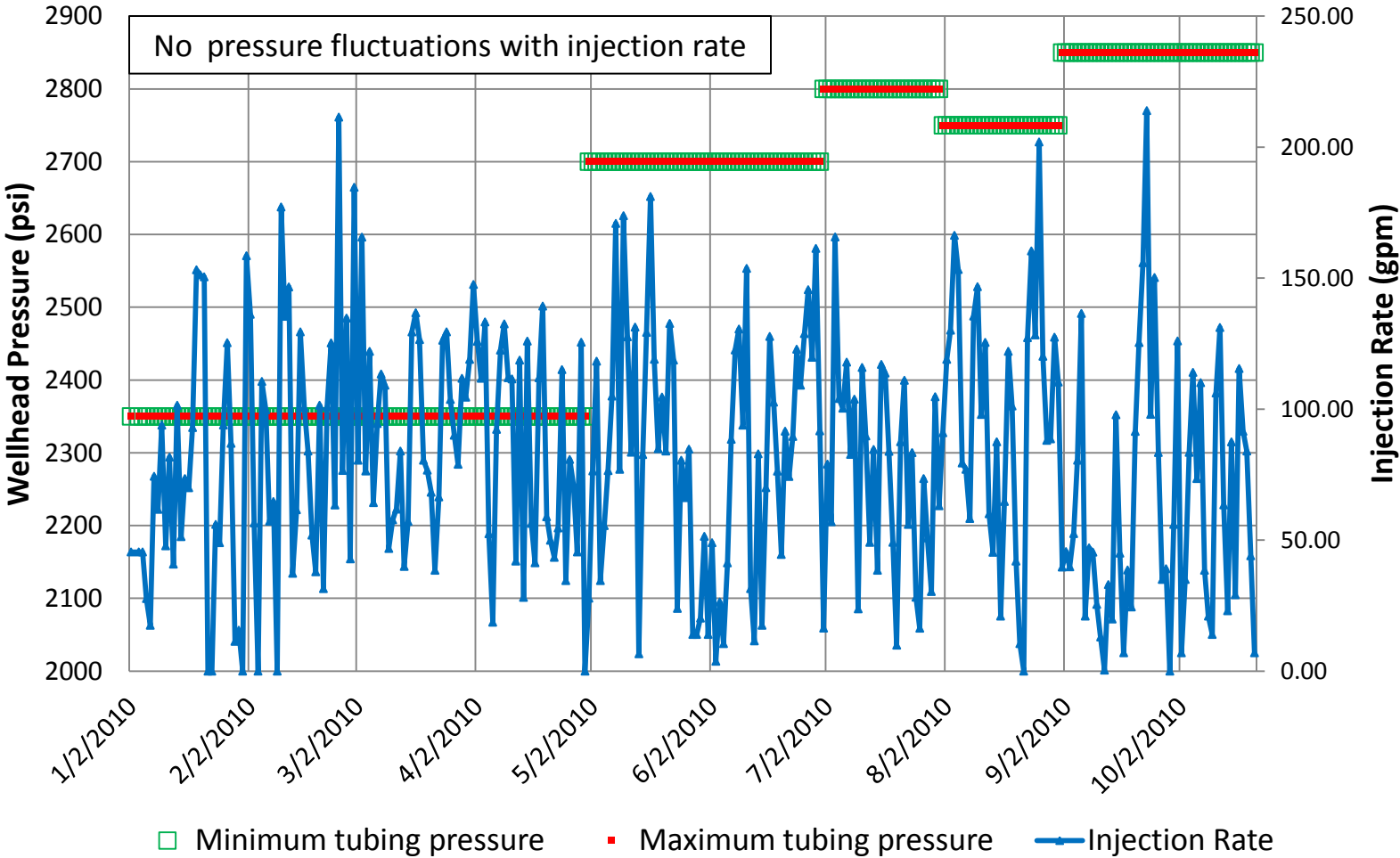


FIGURE E-19: E W MOORE ESTATE 1-22 SWD OPERATIONAL DATA OVERVIEW PLOT



**FIGURE E-20: WAYNE L EDGMON NO. 1 SWD OPERATIONAL DATA OVERVIEW PLOT**

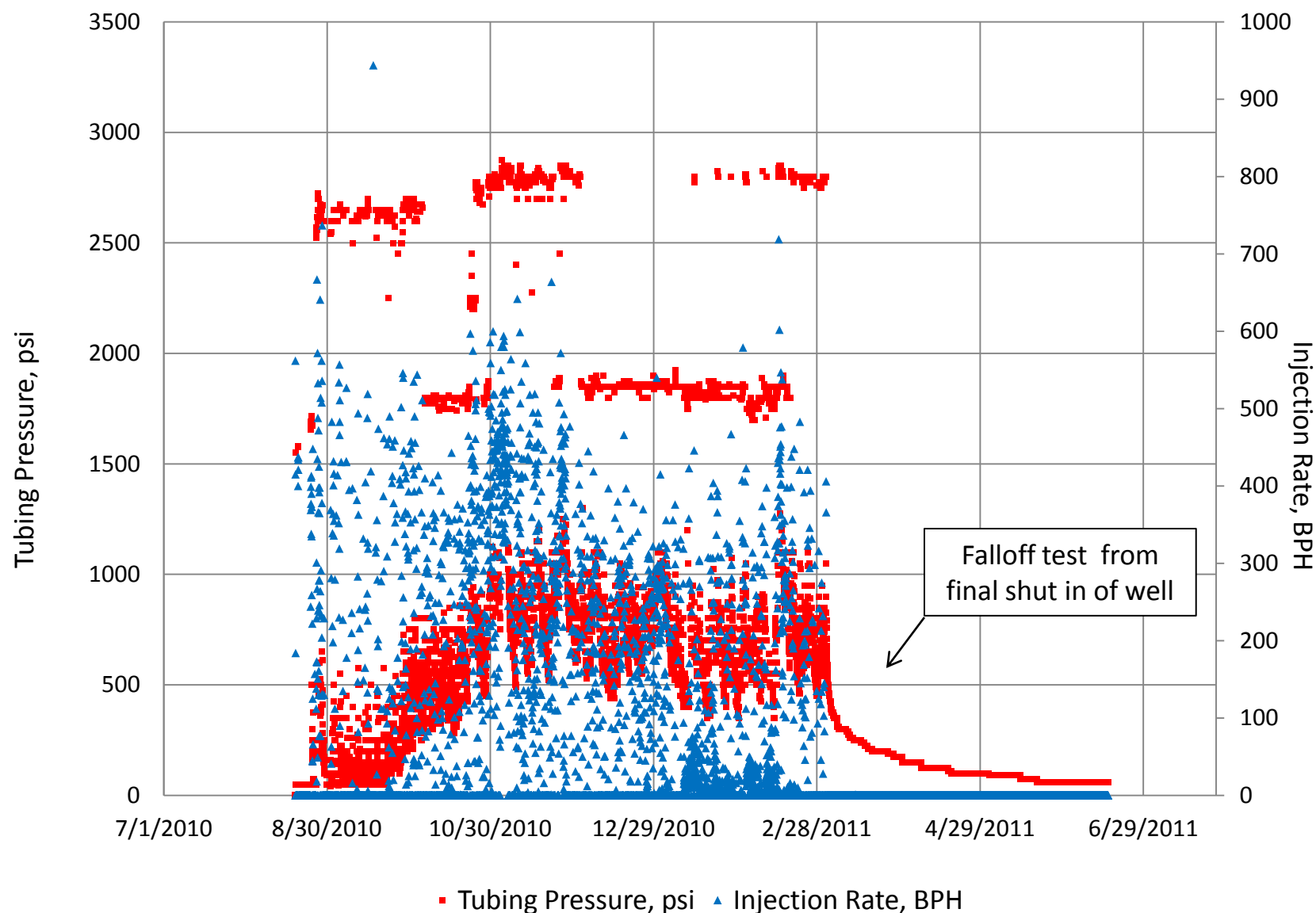


FIGURE E-21: TRAMMEL 7-13 1-8D SWD OPERATIONAL DATA OVERVIEW PLOT

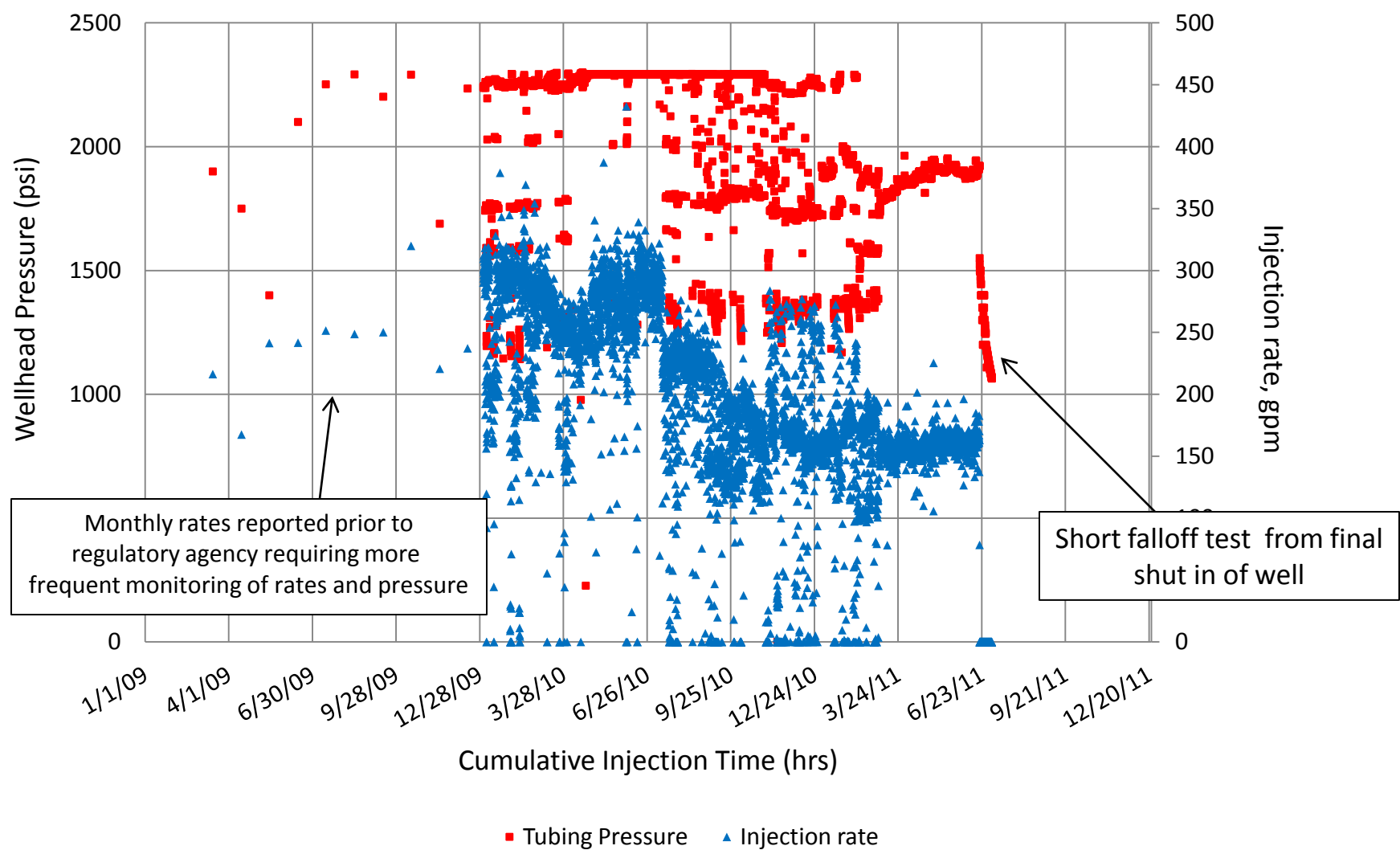


FIGURE E-22: SRE 8-12 1-17 SWD OPERATIONAL DATA OVERVIEW PLOT

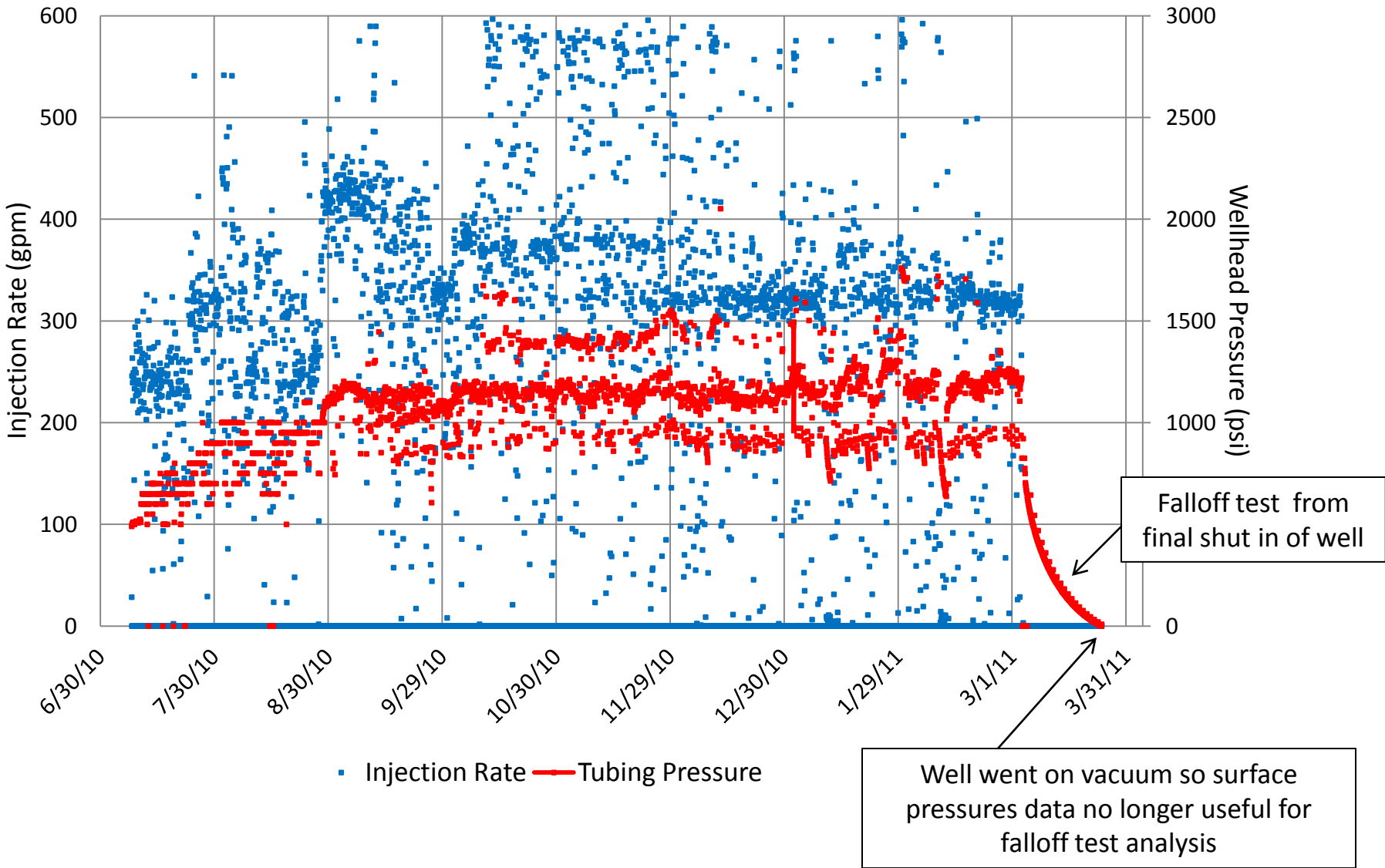
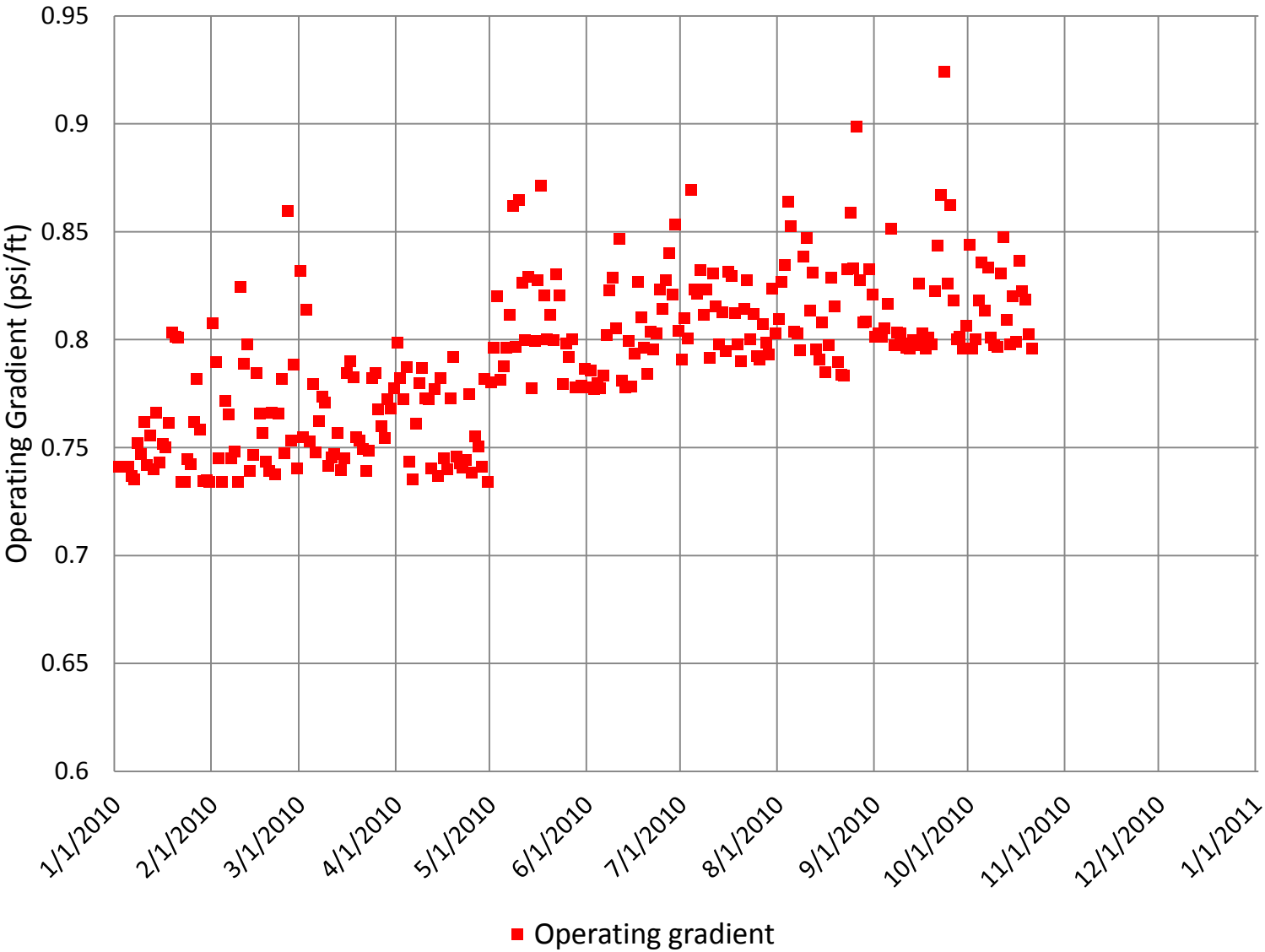
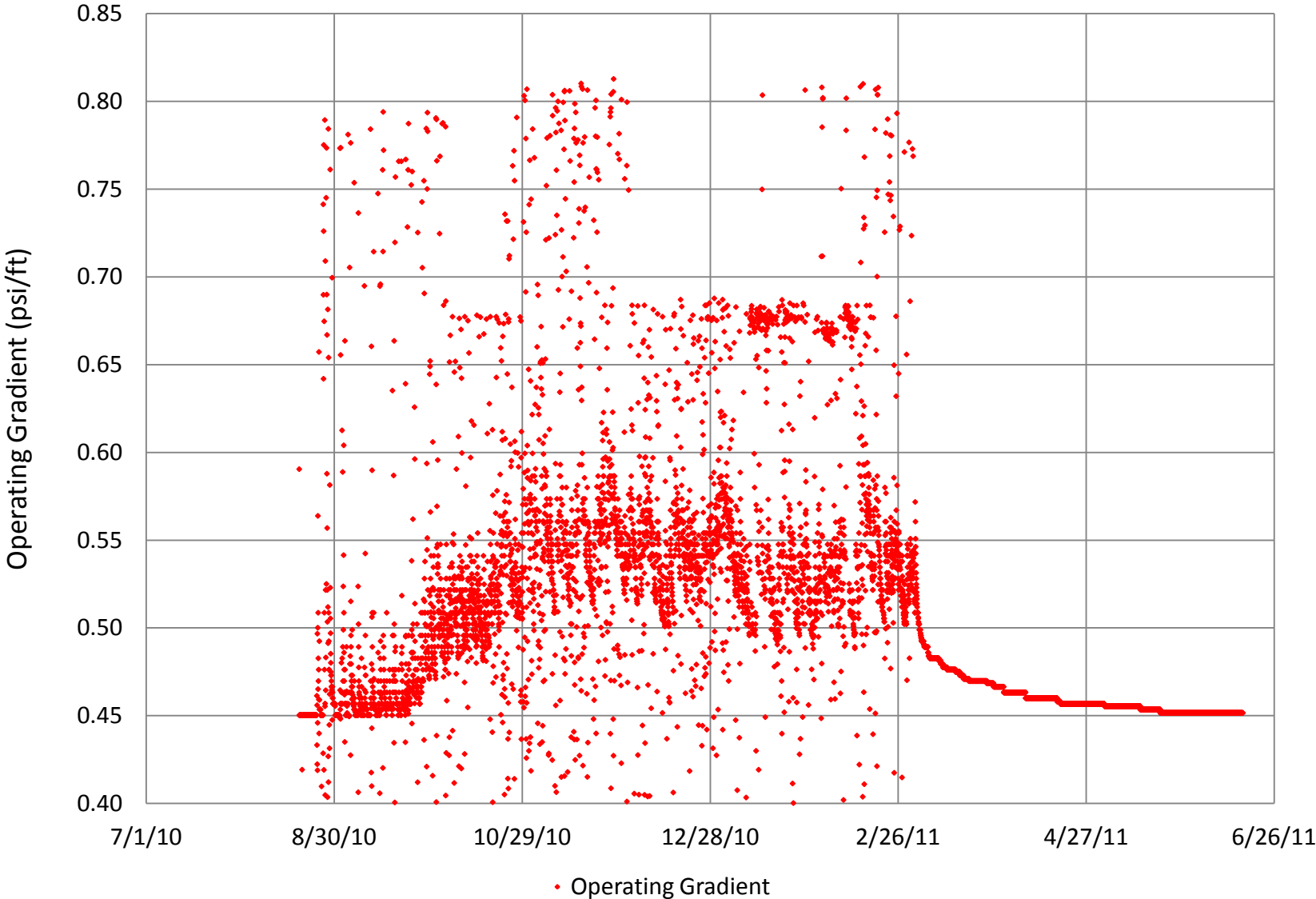


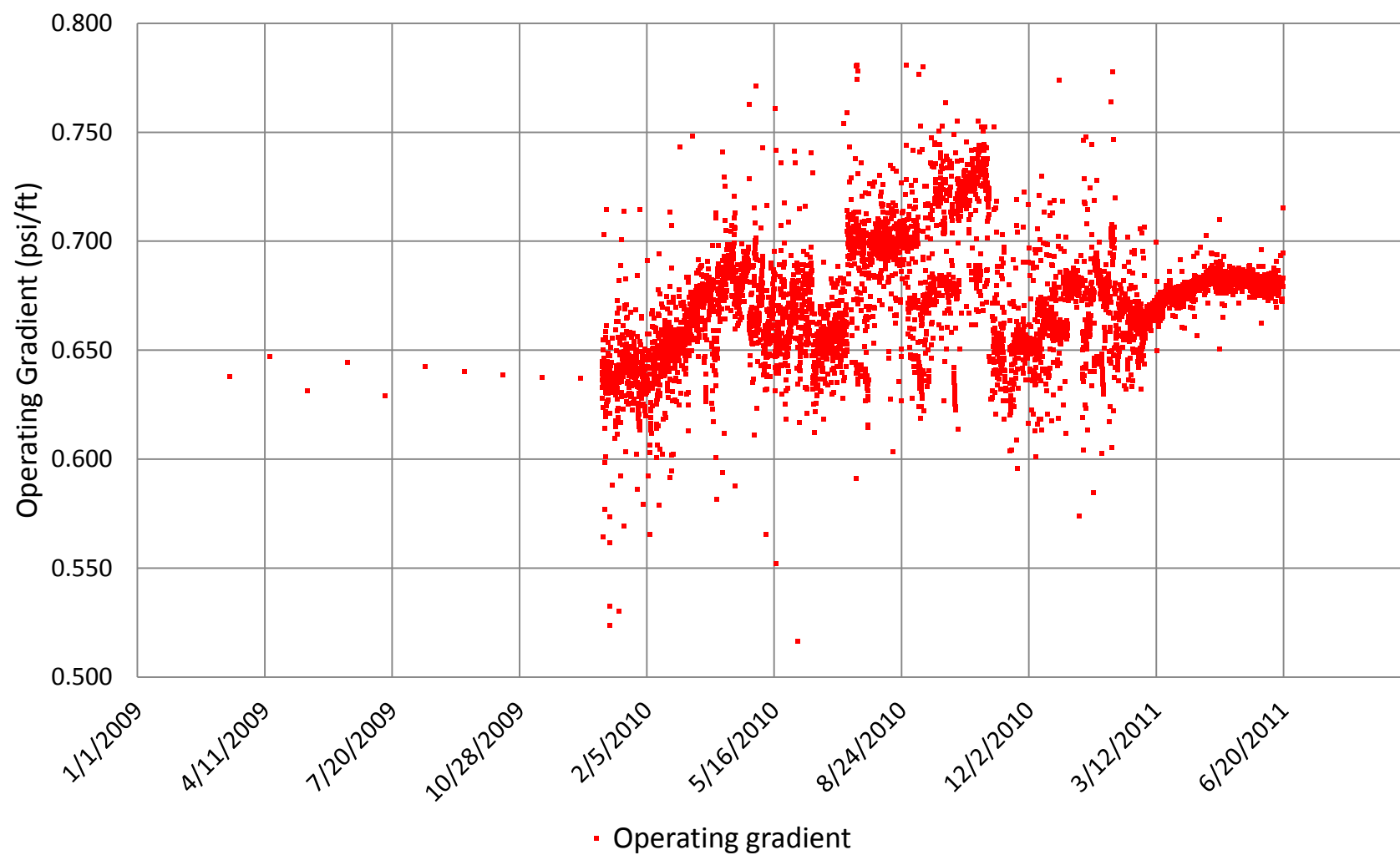
FIGURE E-23: E W MOORE ESTATE 1-22 SWD PRESSURE GRADIENT PLOT



**FIGURE E-24: WAYNE L EDGMON NO. 1 SWD PRESSURE GRADIENT PLOT**



**FIGURE E-25: TRAMMEL 7-13 1-8D SWD PRESSURE GRADIENT PLOT**





**FIGURE E-26: SRE 8-12 1-17 SWD PRESSURE GRADIENT PLOT**

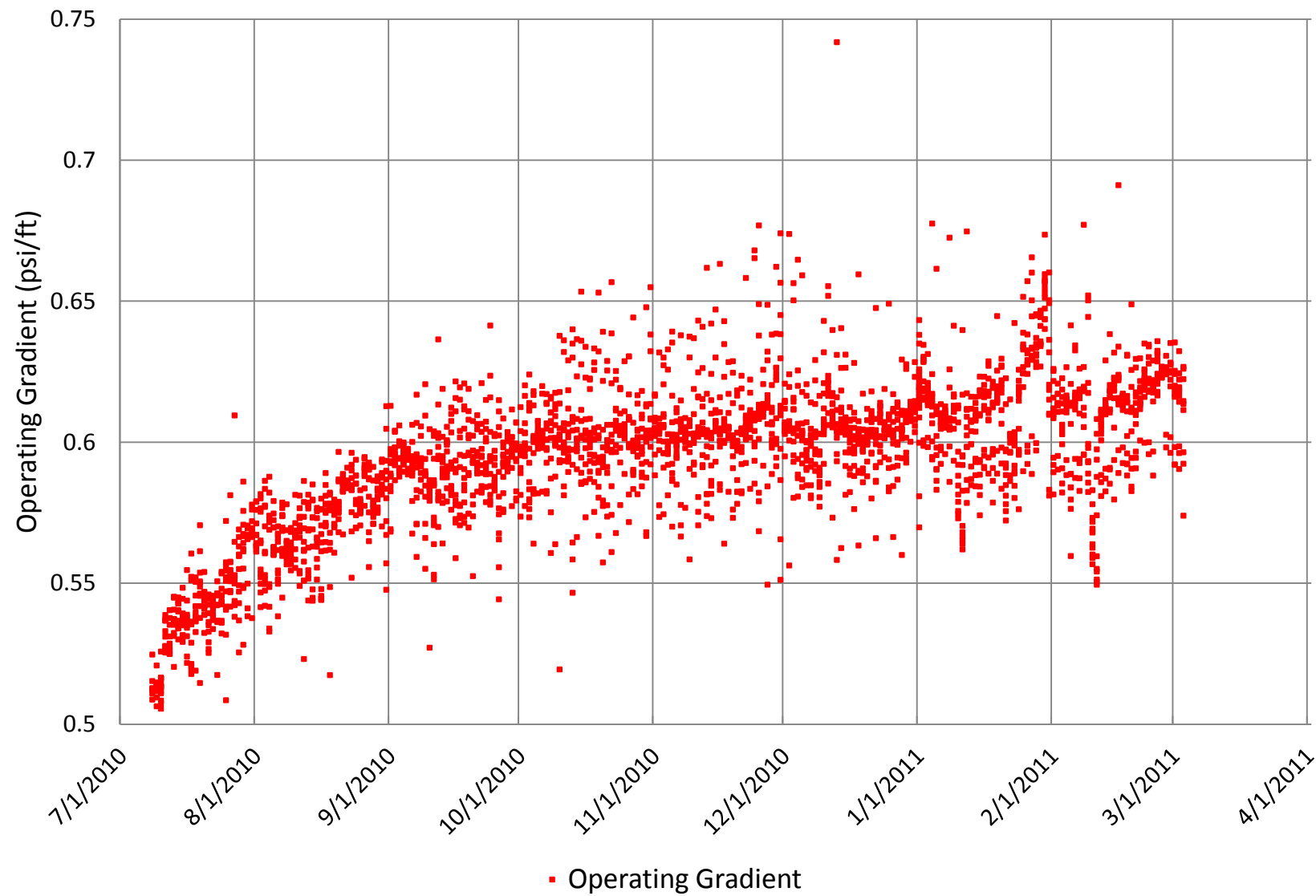


FIGURE E-27: E W MOORE ESTATE 1-22 HALL INTEGRAL AND DERIVATIVE PLOT

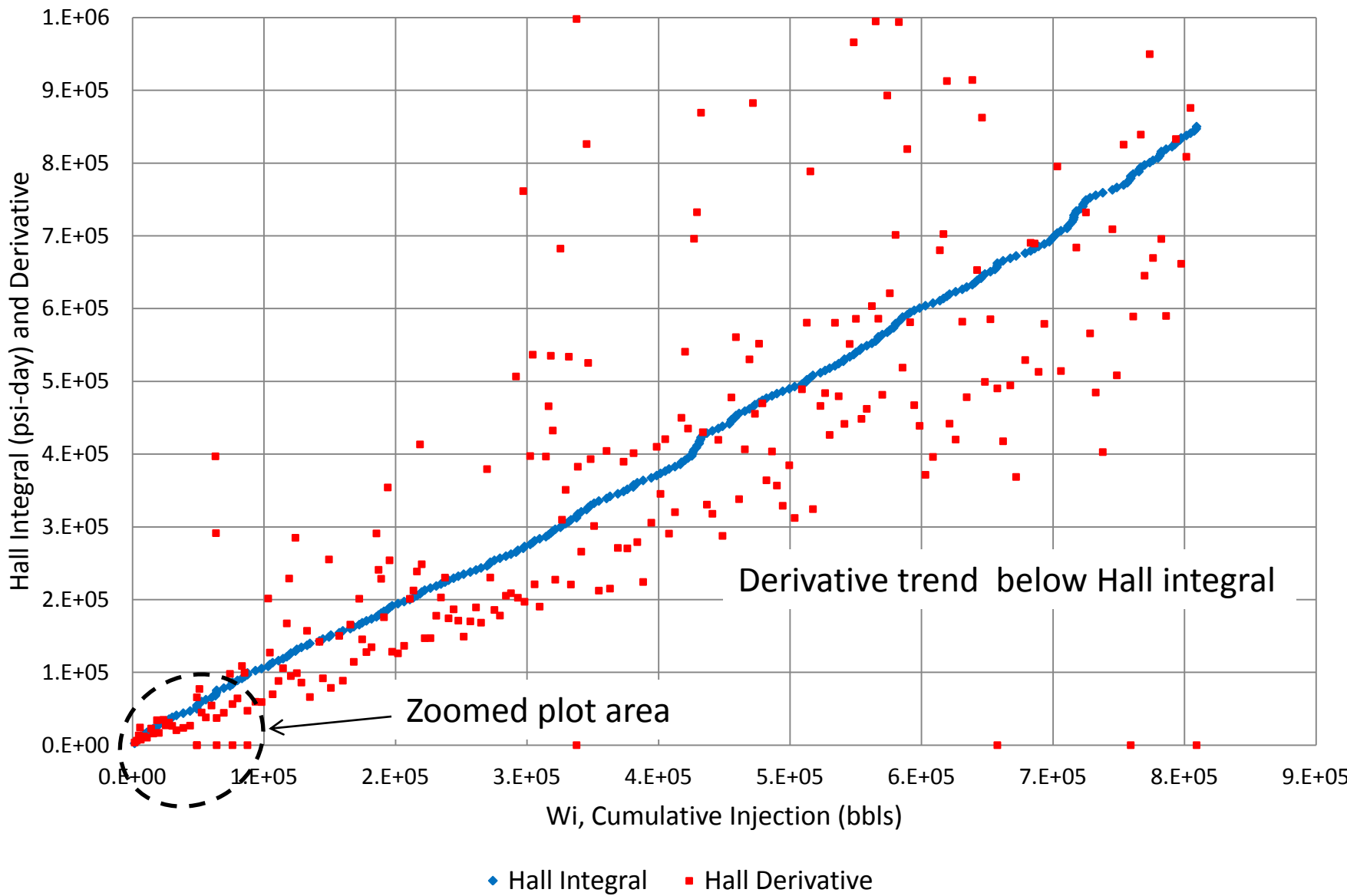


FIGURE E-28: E W MOORE ESTATE 1-22 SWD ZOOMED PLOT OF EARLY TIME DATA

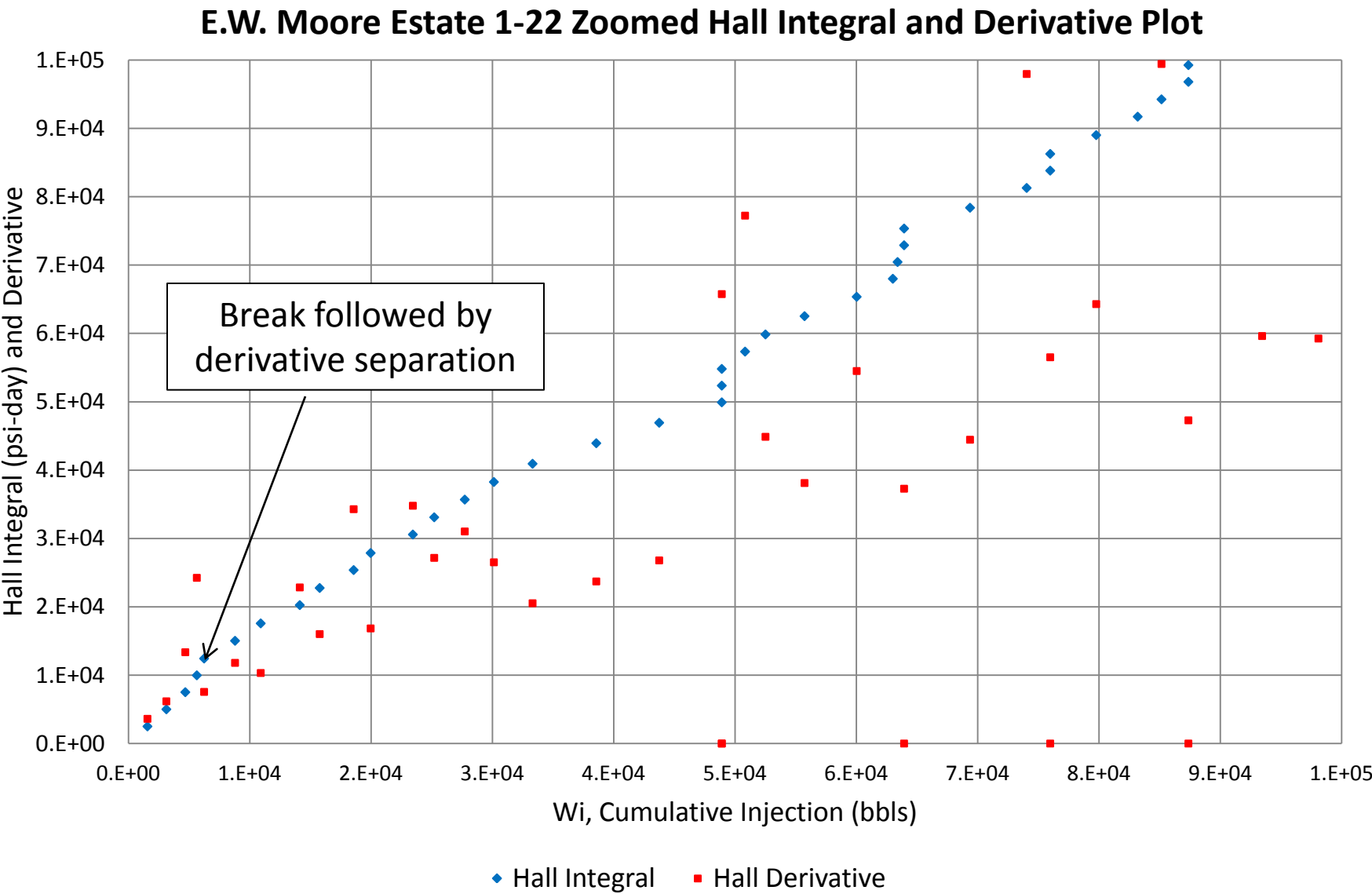


FIGURE E-29: TRAMMEL 7-13 1-8D SWD HALL INTEGRAL AND DERIVATIVE PLOT

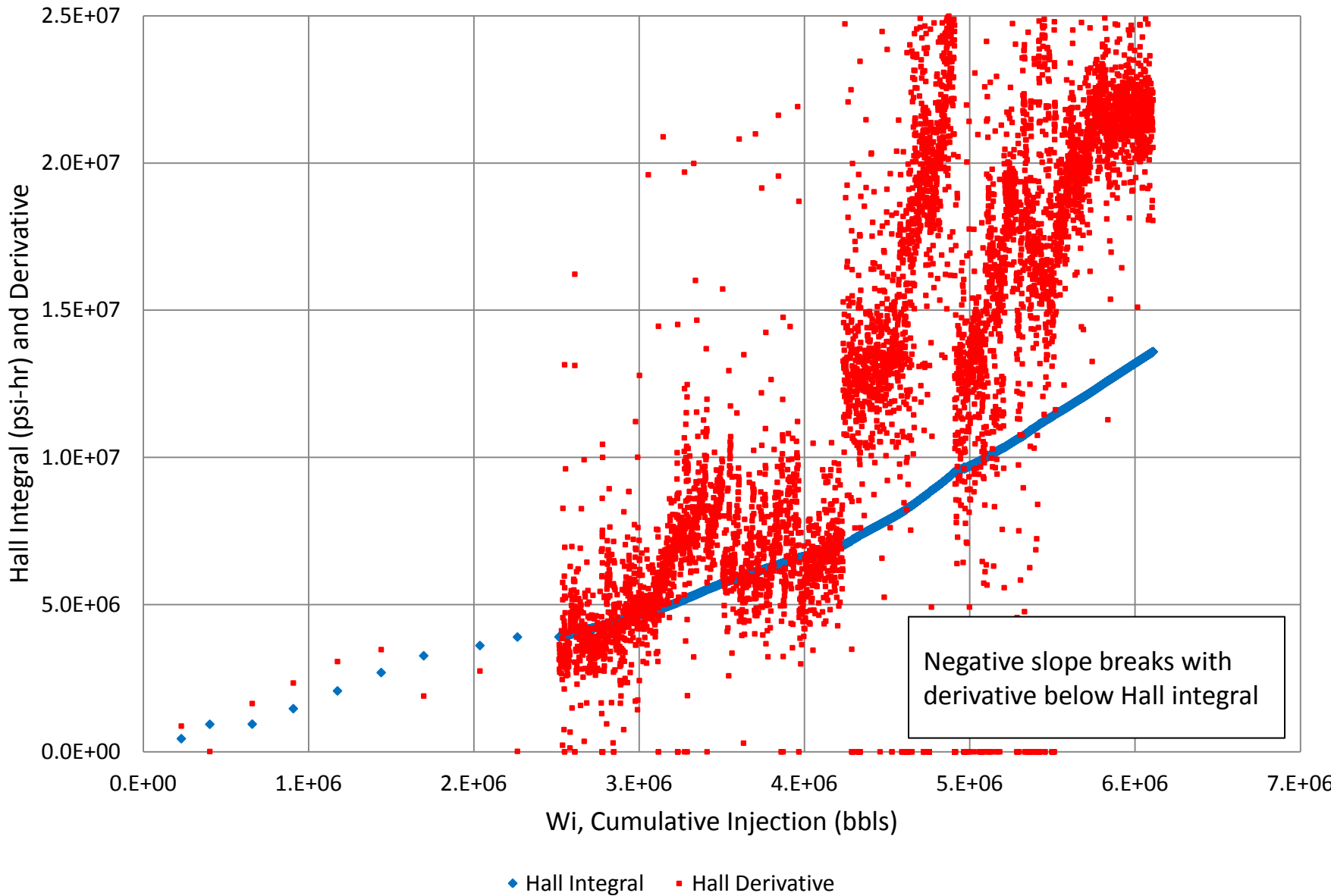
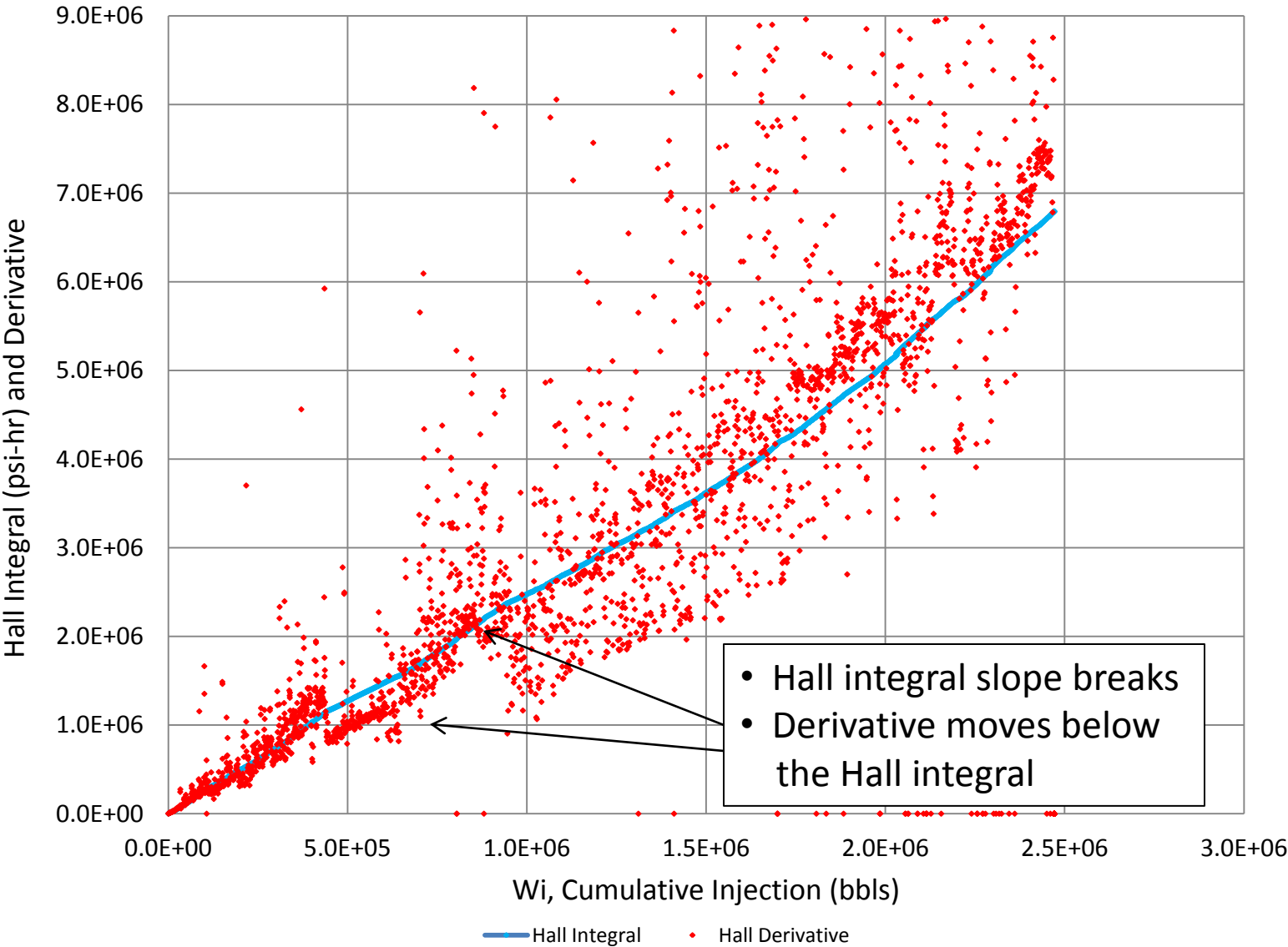


FIGURE E-30: SRE 8-12 1-17 SWD HALL INTEGRAL AND DERIVATIVE PLOT



**FIGURE E-31: SRE 8-12 1-17 SWD ZOOMED PLOT OF EARLY TIME DATA**

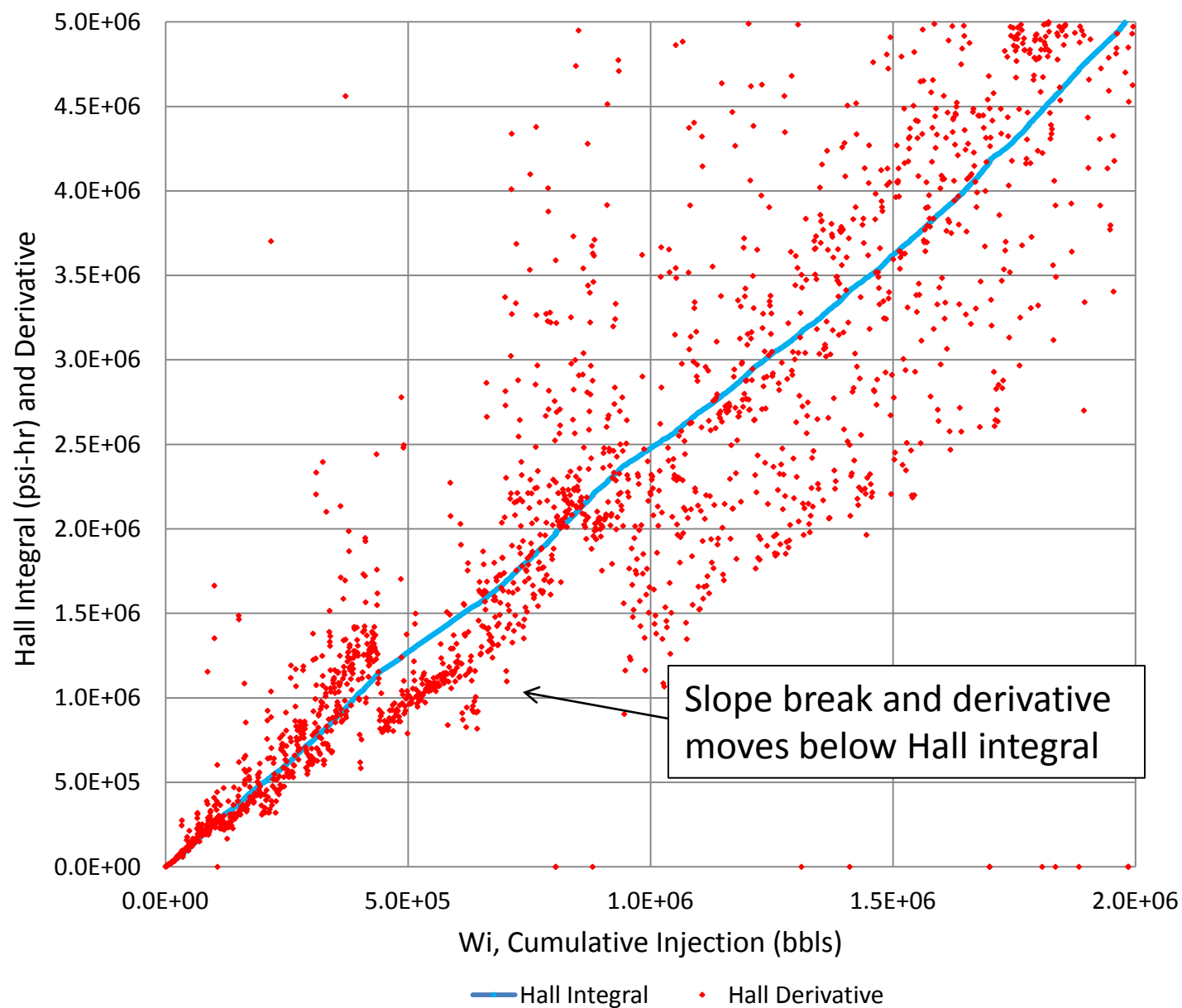


FIGURE E-32: E W MOORE ESTATE 1-22 SWD SILIN SLOPE PLOT



FIGURE E-33: TRAMMEL 7-13 1-8D SWD SILIN SLOPE PLOT

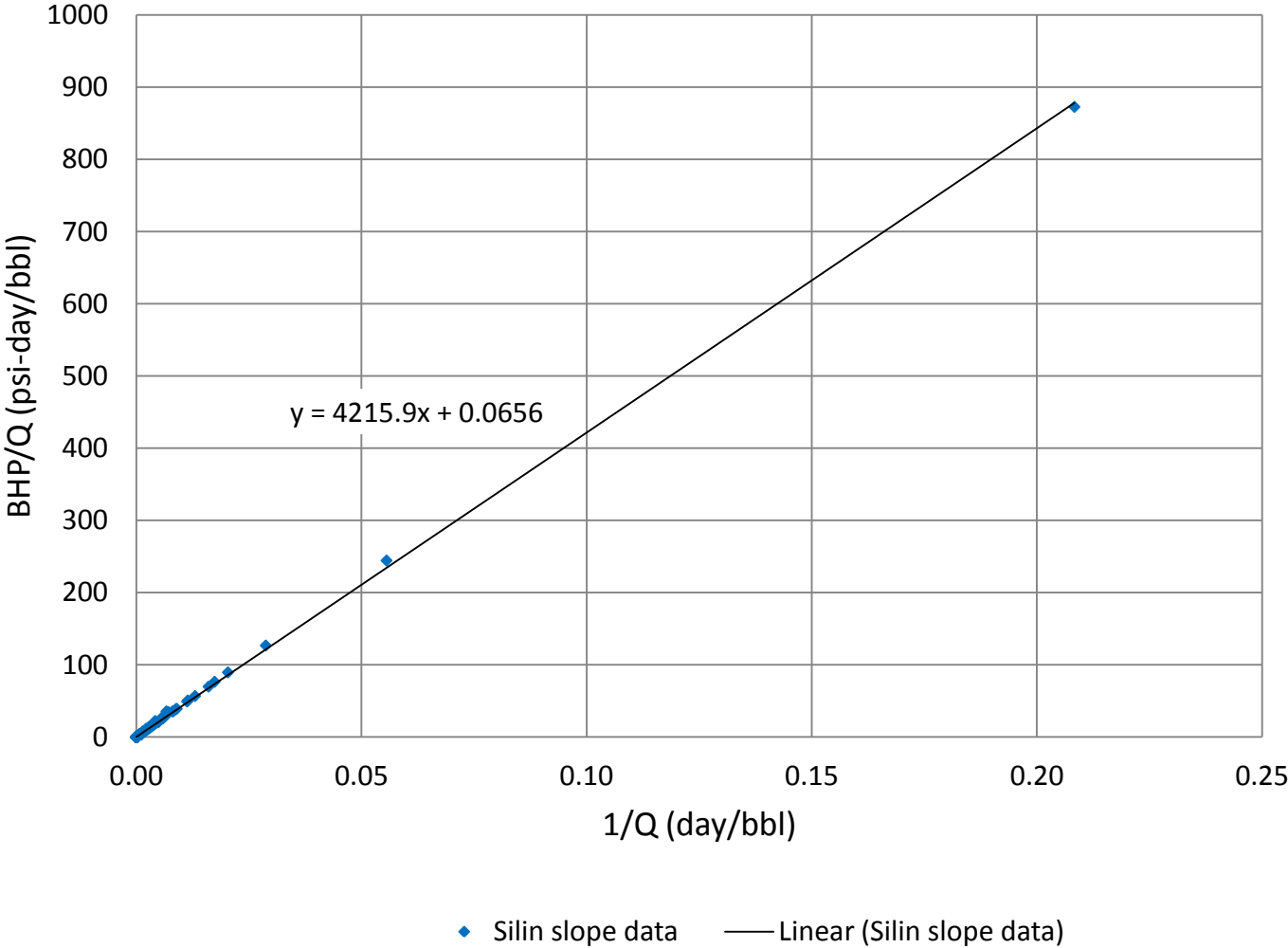




FIGURE E-34: SRE 8-12 1-17 SWD SILIN SLOPE PLOT

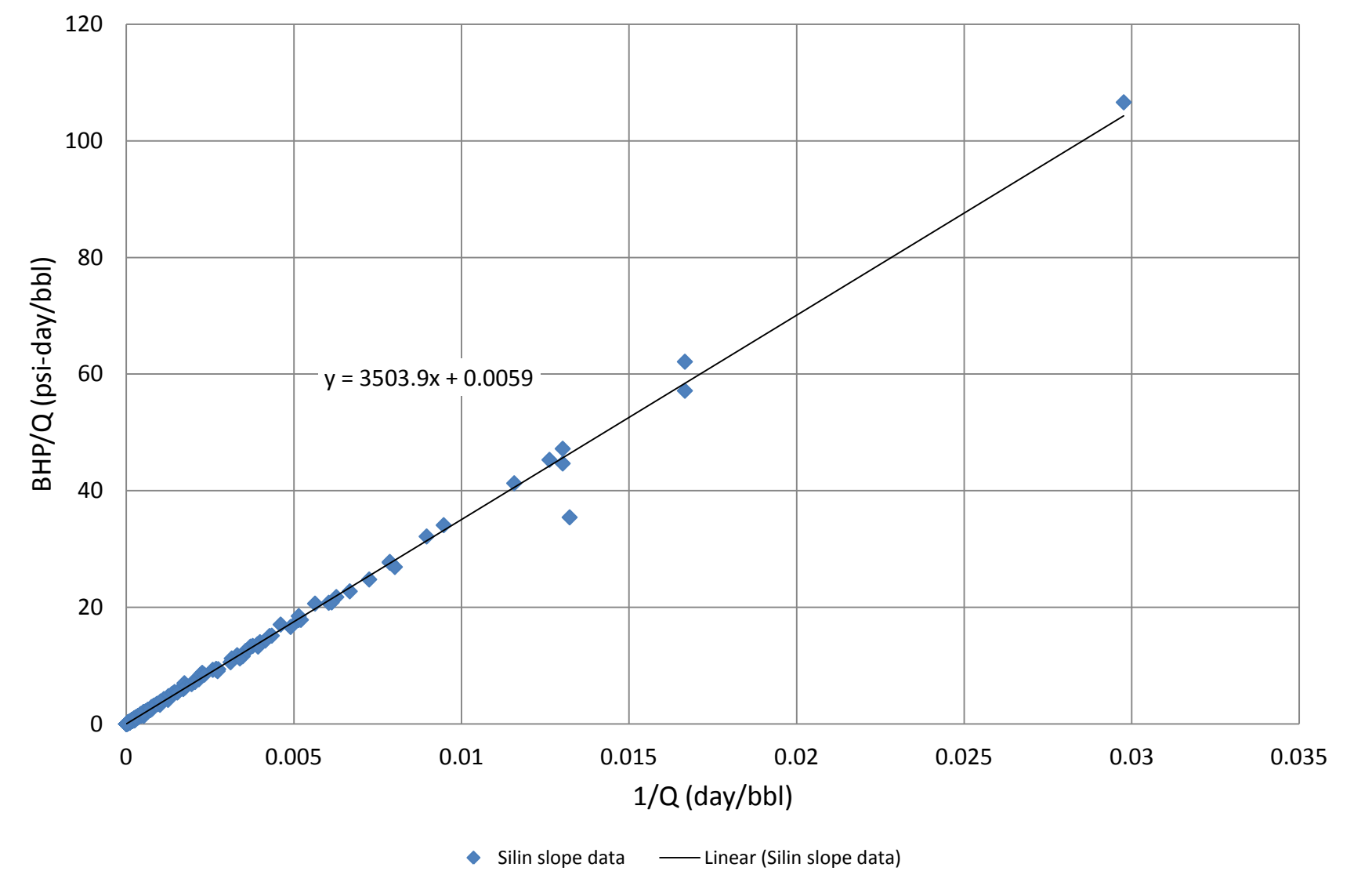


FIGURE E-35: E W MOORE ESTATE 1-22 SWD TANDEM PLOT

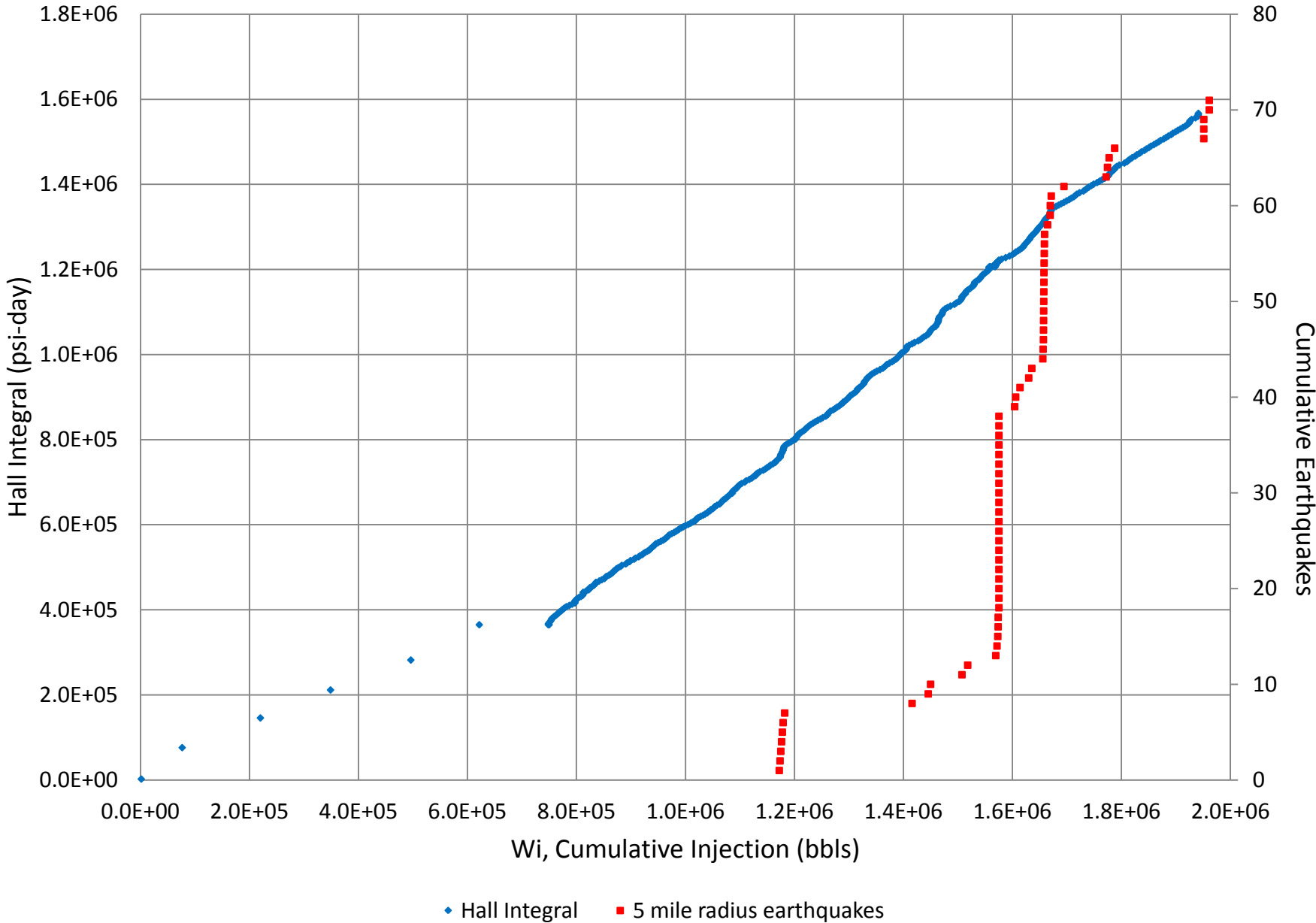


FIGURE E-36: TRAMMEL 7-13 1-8D SWD TANDEM PLOT

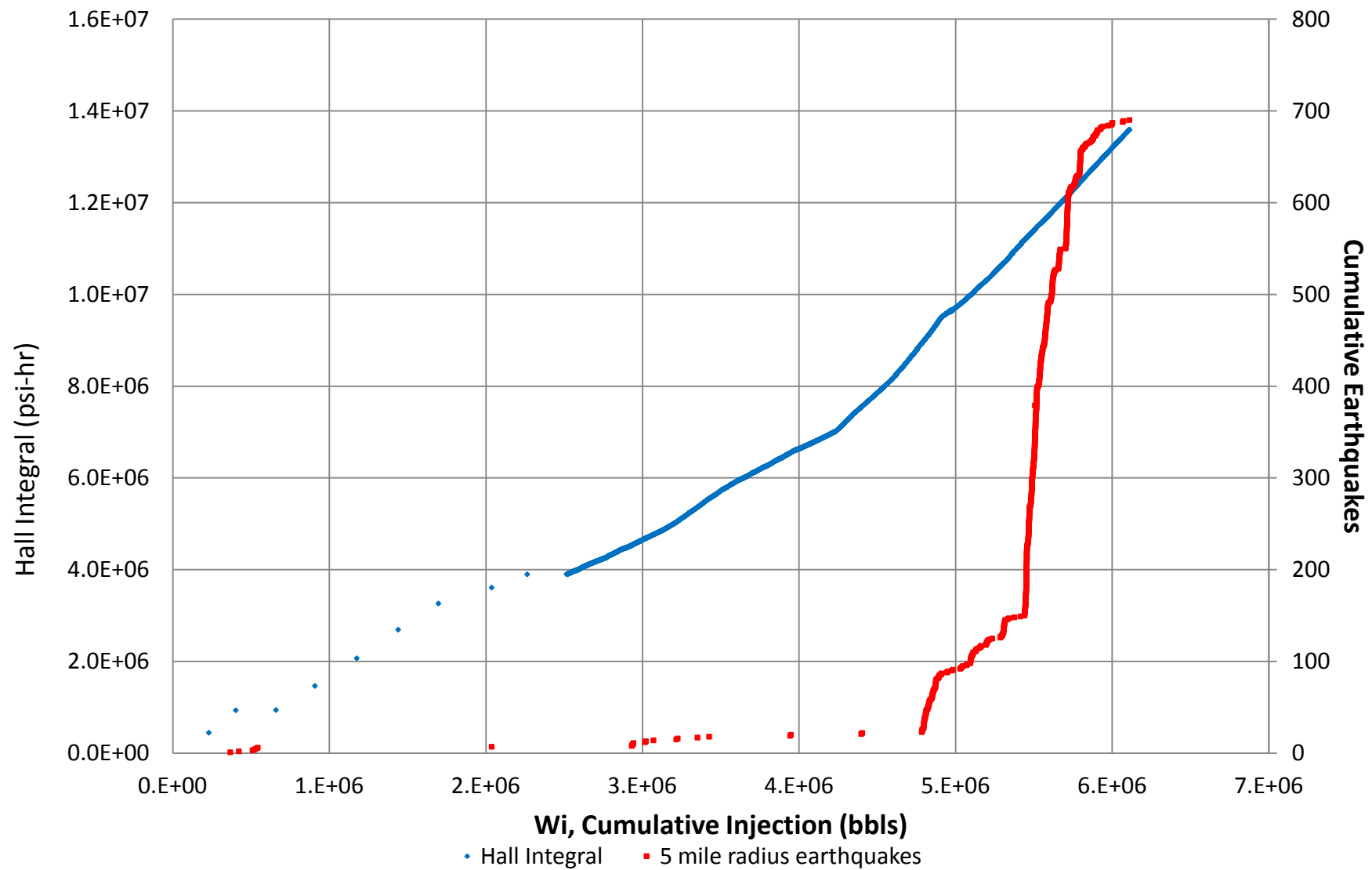
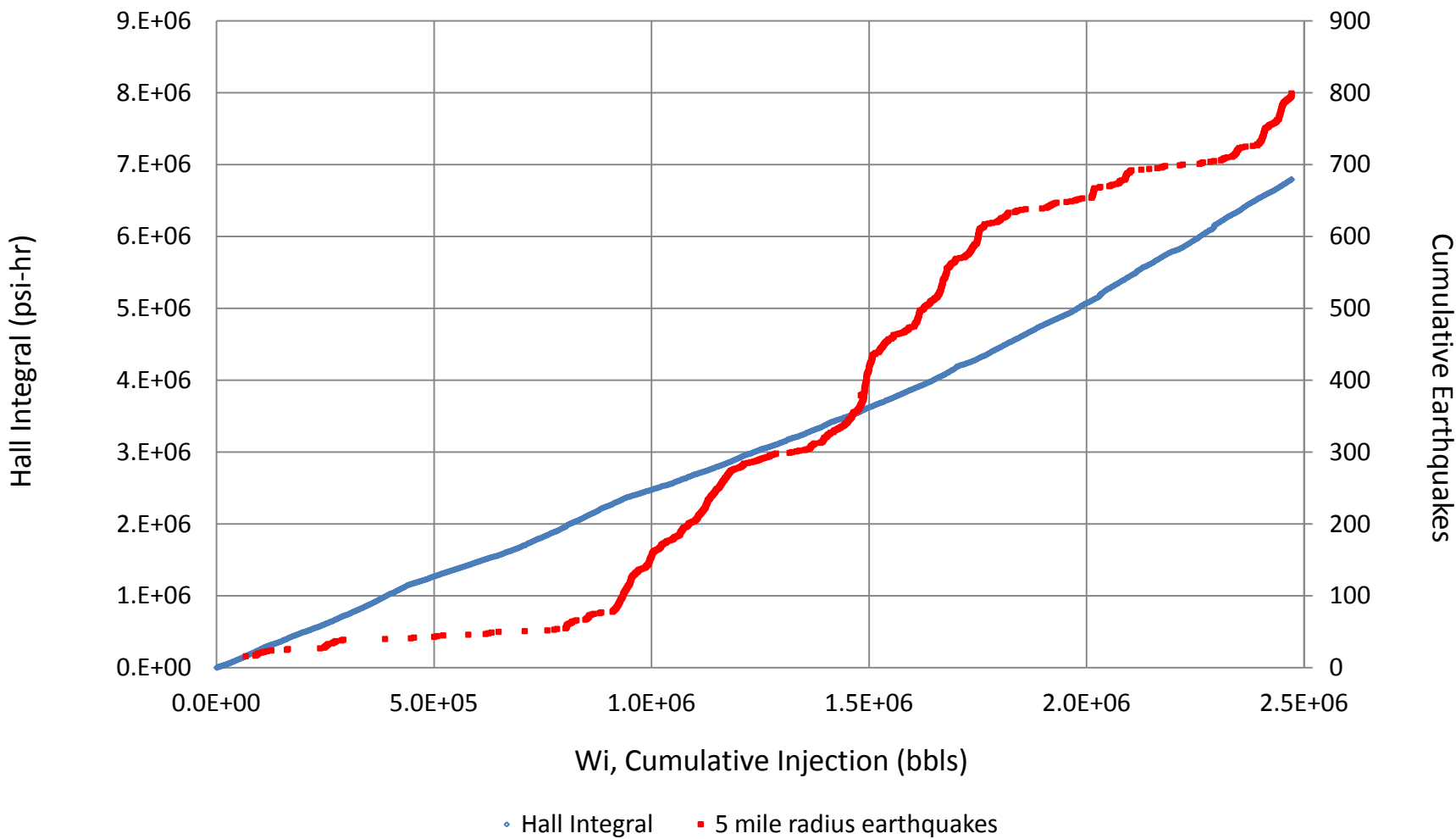
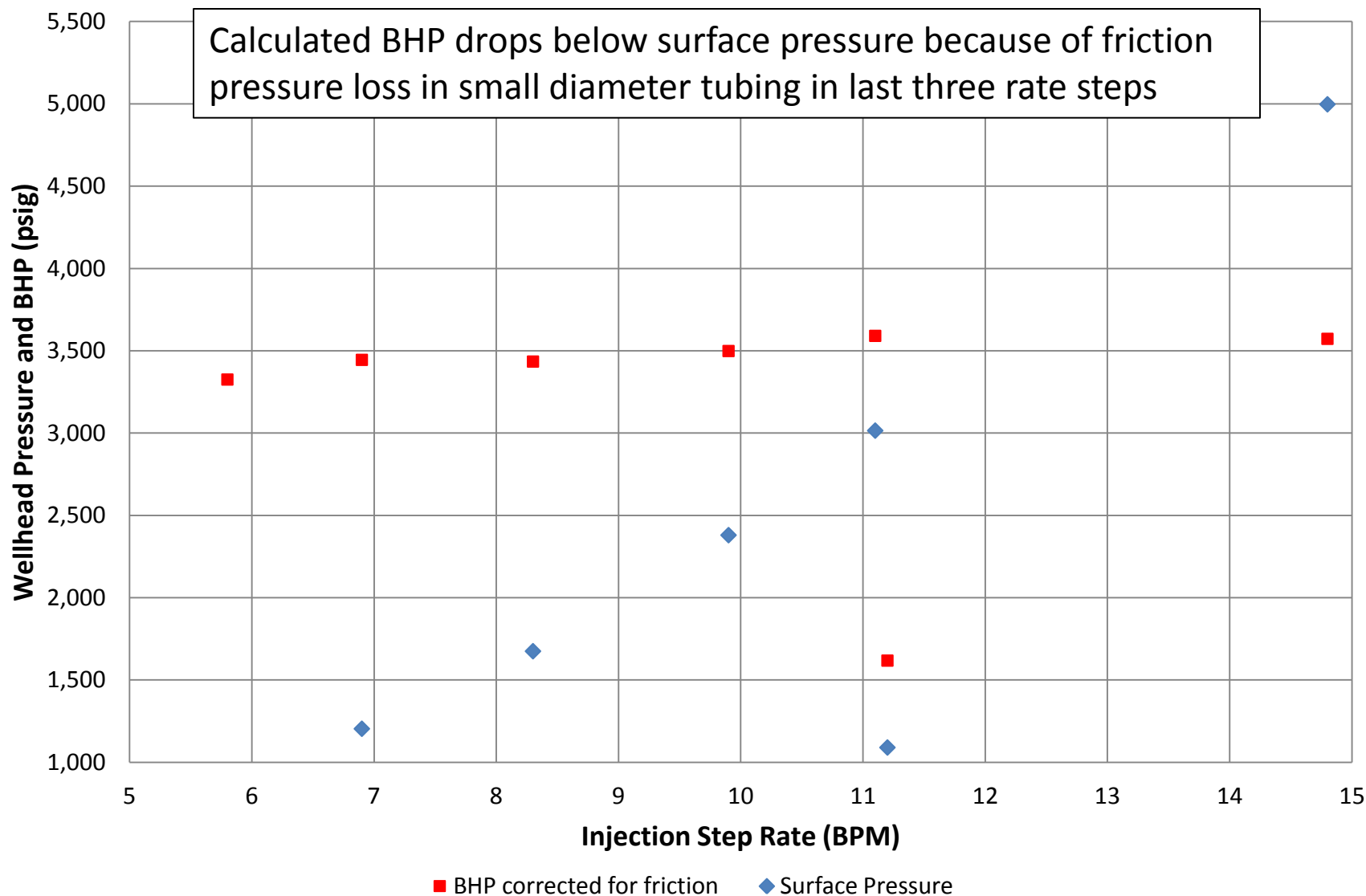


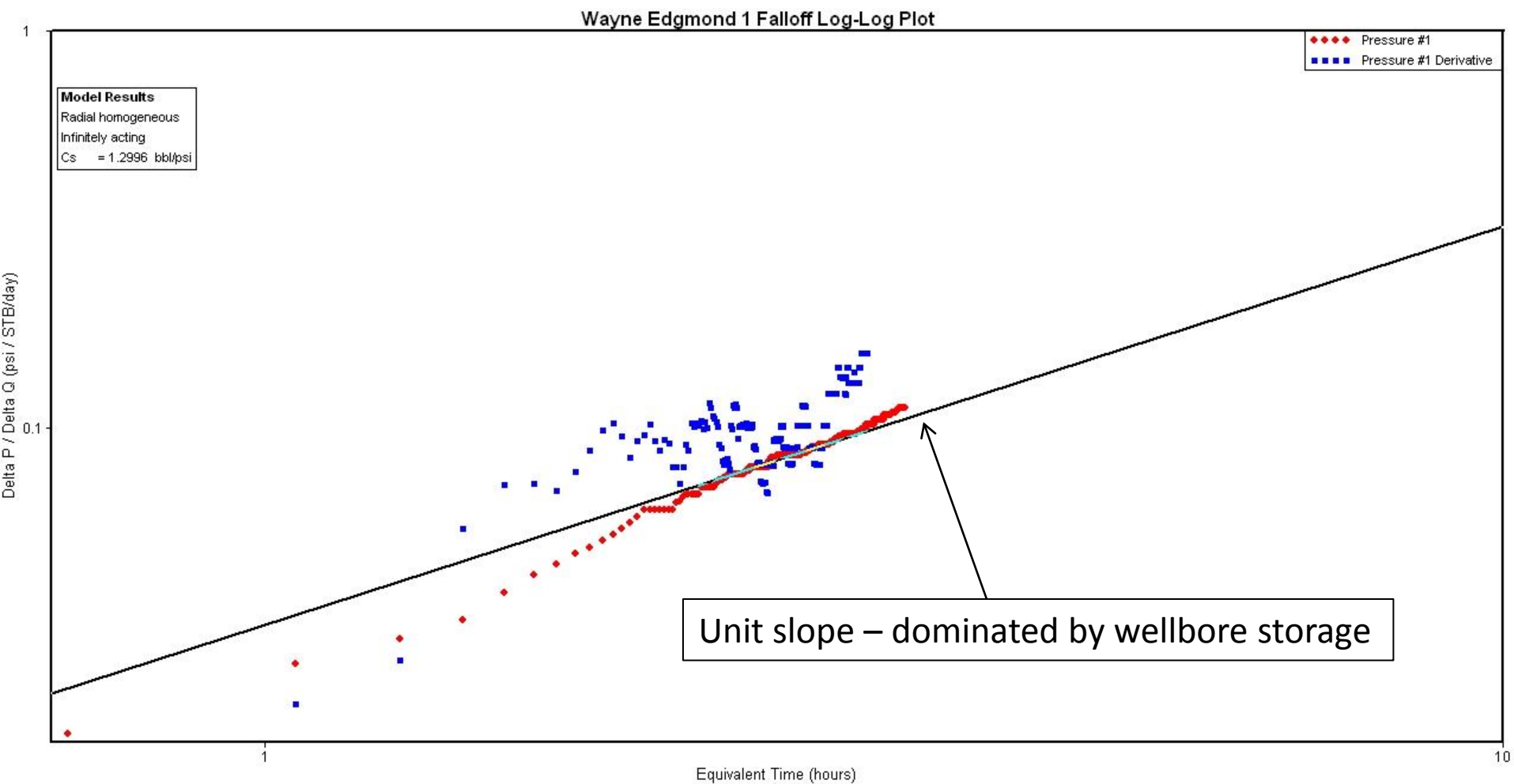
FIGURE E-37: SRE 8-12 1-17 SWD TANDEM PLOT



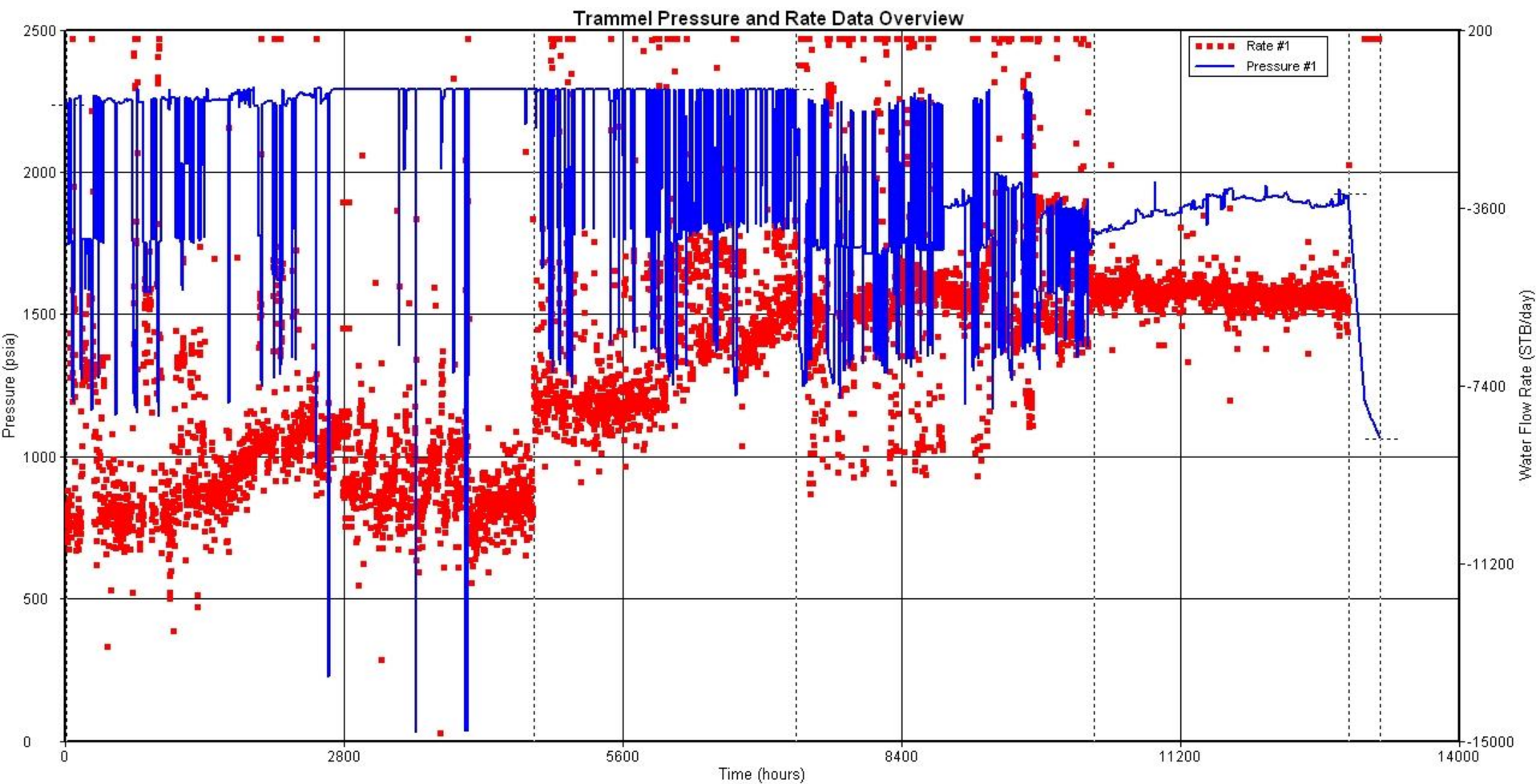
**FIGURE E-38: WAYNE L EDGMON NO. 1 – STEP RATE TEST (INJECTIVITY TEST)**  
**BHP CALCULATED WITH FRICTION FACTOR C = 150**



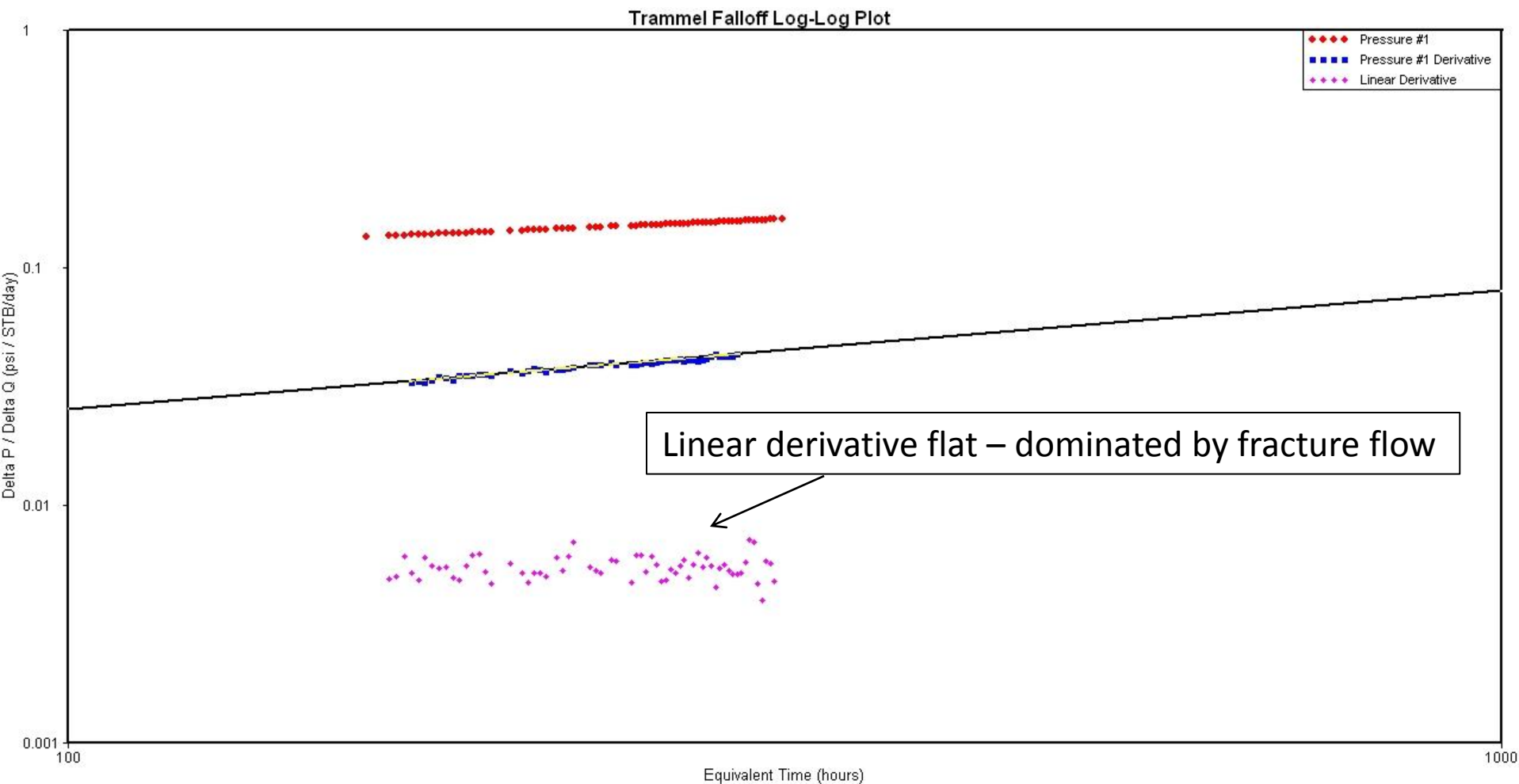
**FIGURE E-39: WAYNE L EDGMON NO. 1 SWD LOG-LOG PLOT OF FINAL FALLOFF  
EQUIVALENT TIME FUNCTION (VARIABLE RATE PRIOR TO SHUT-IN)**



**FIGURE E-40: TRAMMEL 7-13 1-8D SWD SHUT-IN PERIODS AND FINAL FALLOFF**

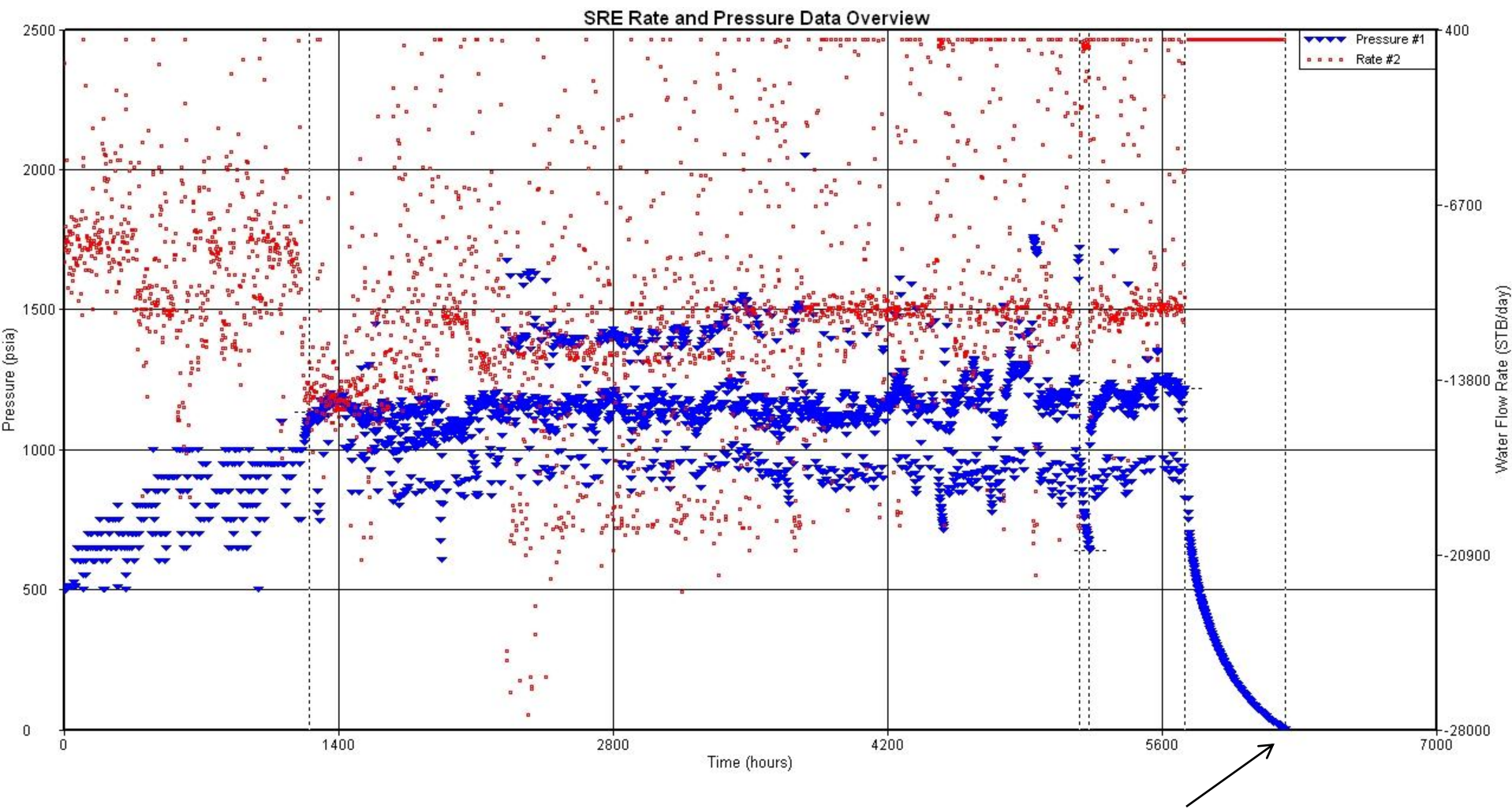


**FIGURE E-41: TRAMMEL 7-13 1-8D SWD LOG-LOG PLOT OF FINAL FALLOFF  
EQUIVALENT TIME FUNCTION (VARIABLE RATE)**

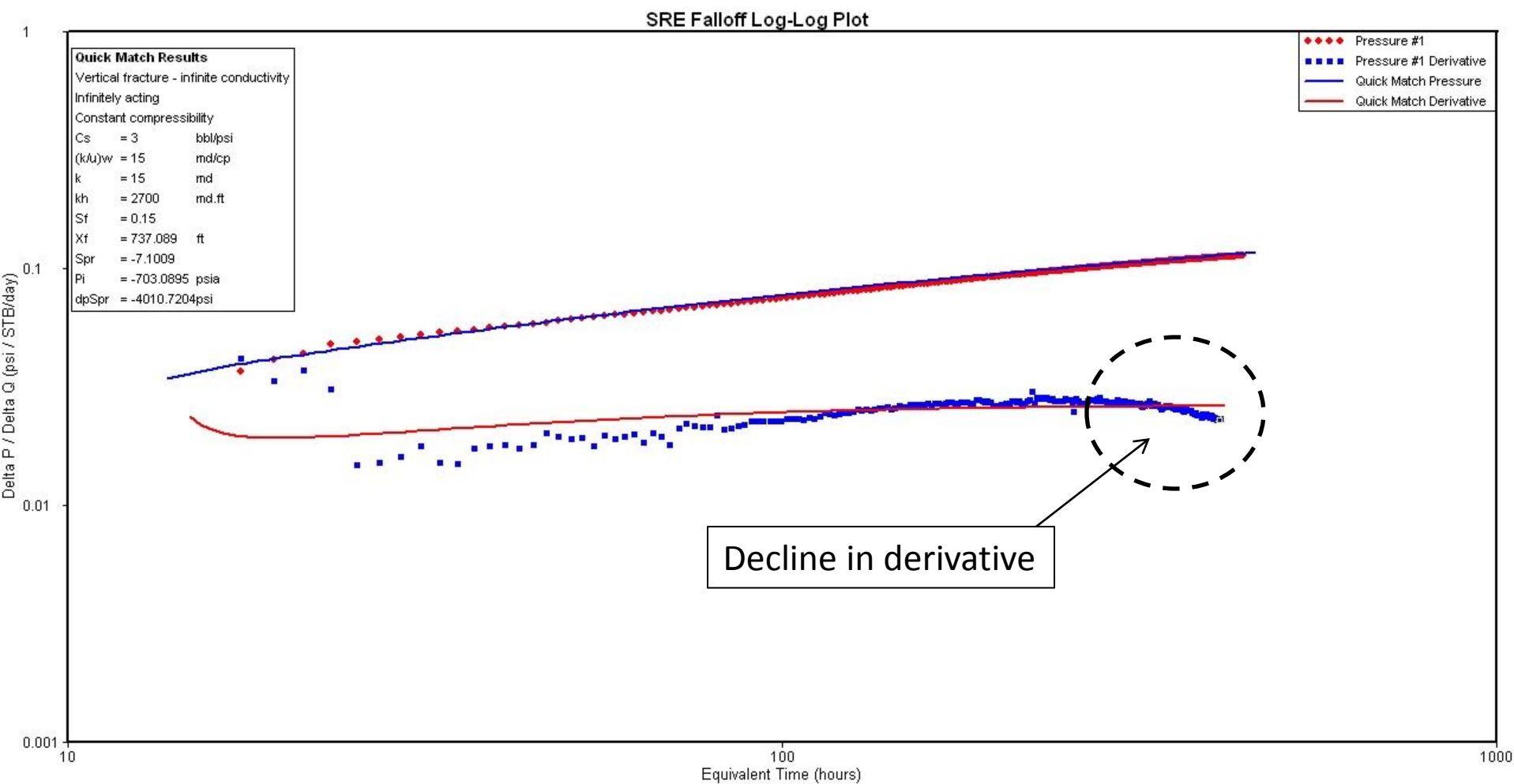




**FIGURE E-42: SRE 8-12 1-17 SWD SHUT-IN PERIODS AND FINAL FALLOFF**



**FIGURE E-43: SRE 8-12 1-17 SWD LOG-LOG PLOT OF FINAL FALLOFF  
INFINITE CONDUCTIVITY TYPE CURVE MATCH**



Equivalent time function for variable rate

## APPENDIX F: BRAXTON COUNTY, WEST VIRGINIA, CASE STUDY AREA

|   |     |
|---|-----|
| Background .....  | F-1 |
| History of Seismicity.....  | F-1 |
| Geologic Setting .....  | F-2 |
| Oil and Gas Activity .....  | F-2 |
| Vicinity Disposal Wells .....   | F-2 |
| Data Collected .....  | F-2 |
| Data Reviewed .....   | F-3 |
| Operational Analysis Plots and Observations.....                        | F-4 |
| Actions taken by UIC regulatory agency in Braxton County, WV area ..... | F-5 |
| References .....  | F-5 |

### BACKGROUND

In 2010, a series of earthquakes occurred in Braxton County, West Virginia, (Figure F-1). The relationship between the earthquakes and a nearby Class II disposal well was investigated by the West Virginia Department of Environmental Protection Office of Oil and Gas.

### HISTORY OF SEISMICITY

Only one low level earthquake in 2000 was recorded in the ANSS database, prior to the events starting in 2010. All six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERI and PDE), were searched. A summary of the recent Braxton County earthquakes, within a twelve mile area<sup>18</sup> of the case study well discussed below, is provided in the Table F-1 below and a timeline of events is shown on Figure F-2. A zoomed map area of the disposal well and earthquake activity is included on Figure F-3.

TABLE F-1: BRAXTON AREA SEISMICITY THROUGH 1/31/2012

| Year | Starting Date | Number of Events | Magnitude |      |      | Ending Date |
|------|---------------|------------------|-----------|------|------|-------------|
|      |               |                  | Min.      | Avg. | Max. |             |
| 2000 | 10/16/2000    | 1                | 2.5       | 2.5  | 2.5  | 10/16/2000  |
| 2010 | 4/4/2010      | 8                | 2.2       | 2.6  | 3.4  | 7/25/2010   |
| 2011 |               | 0                |           |      |      |             |
| 2012 | 1/10/2012     | 1                | 2.8       | 2.8  | 2.8  | 1/10/2012   |

<sup>18</sup> The search area was increased owing to the lack of location certainty, occasioned by the poor density of seismometers.

## *GEOLOGIC SETTING*

Braxton County is located in the Appalachian basin, on the eastern edge of the Paleozoic Marcellus shale and Devonian Trenton gas plays, (Figure F-1). The Marcellus outcrops in eastern West Virginia, though this is not shown in Figure F-1 (Avary, 2011).

The Marcellus unconformably overlies the Onondaga Limestone (Figures F-4, Avary, 2011 and F-5, WVGES, 2011), which is an easily recognizable marker on logs and seismic surveys. The Marcellus is predominantly siliceous, with mixed muscovite and illite, and minor amounts of pyrite and kaolinite (Boyce and Carr, 2009).

## *OIL AND GAS ACTIVITY*

Gas production in the Marcellus Shale of West Virginia started in 2005, with Braxton County drilling starting in 2006. The Elk Valley Land Corp 626407 Class II brine disposal well was initially completed in the Marcellus shale as a gas production well. The vertical well was later converted to disposal into the same interval.

## *VICINITY DISPOSAL WELLS*

Only one disposal well is currently permitted to inject into the Marcellus in the state and was the focus of this case study. Injection activities began in the Elk Valley Land Corp SWD in March 2009 about one year prior to the start of seismic events. A zoomed map area of the disposal well and earthquake activity in Braxton County is included on Figure F-3. Figure F-6 is a wellbore schematic illustrating the construction and completion information for the Elk Valley Land Corp Well No. 626407. Additional details are summarized below:

*Elk Valley Land Corp 626407*; UIC Permit 2D0072539; Completed 08/07/2007; Initial injection March 2009; Authorized injection zone 6,472'-6,524'; Marcellus.

## *DATA COLLECTED*

The West Virginia Department of Environmental Protection (WVDEP) Office of Oil and Gas provided the permitting and operational data used in analysis of the Elk Valley Land Corp SWD. Annual report data included monthly injection volumes, maximum injecting tubing pressure, maximum shut-in tubing pressure, and hours operated during the month. Permit information indicated that the vertical well was initially fractured with a total of 355,000 pounds of sand and 14,398 barrels of water prior to being converted to a disposal well.

Permit application data provided tubing dimensions and depth (2 7/8", 6.5 lb/ft, at 6395', inner diameter 2.441"). The chlorides in the fluid analysis included in the permitting documentation ranged from 0-250,000 mg/L.

A step rate test was performed on the Elk Valley Land Corp SWD in March 2008, prior to injection, and was also included with the permit information. The injection rate started at 0.5 and increased to 5.5 barrels per minute over eight rate steps. Individual steps were primarily 30 minute intervals, except for the last step held for 3 hours. A total of 1,410 barrels was injected into the well during 6.5 hours of step rate testing. A summary of the rate and tubing pressure measurements is included in Table F-2.

#### *DATA REVIEWED*

Monthly data included hours operated which was used to convert the monthly injection volume to an average injection rate. The operating surface pressure was the average of the maximum injection and maximum shut-in pressures for each month. Surface pressures were converted to approximate bottomhole pressures (BHP) at 6395 feet. To determine friction pressure, the Hazen-Williams friction loss correlation with a friction factor, C, of 100 for steel tubing was used. BHPs were calculated by adding the surface pressure and hydrostatic column of fluid and subtracting the calculated friction pressure loss. A brine specific gravity of 1.125 was used to approximate 100,000 ppm chloride brine. The hydrostatic column of fluid was calculated at 3115 psia. Because the well went on a vacuum an average static reservoir pressure of 2800 psia was assumed for the Hall integral calculation. Four operating data-related plots were prepared including operational overview data plot, operating gradient plot, a Hall integral and derivative plot based on average tubing pressure, and a Silin slope plot.

**TABLE F-2: STEP RATE TEST DATA**

| Injection Tubing Pressure<br>at the End of Each Rate<br>Step (psig) | Average Constant<br>Injection Rate for Rate<br>Step (bbls/min) |
|---|--|
| 150   | 0.5  |
| -235  | 1.0  |
| -220  | 1.5  |
| -120  | 2.0  |
| 400   | 3.0  |
| 1160  | 4.0  |
| 1750  | 5.0  |
| 1900  | 5.5  |

Figure F-7 contains an overview plot of the operational data used in the analysis. Figure F-8 is a plot of the calculated operating bottomhole pressure gradient.

The monthly hours reported indicated that the well did not operate continually throughout the month. The Hall integral and derivative functions are continuous functions from monthly data

using only the hours operated in month for calculation of the functions. For the Hall integral calculations, a static pressure of 2800 psia was assumed, slightly below the calculated hydrostatic BHP. Figure F-9 is a plot of the Hall integral and derivative trend for the disposal well and Figure F-10 contains the Silin slope plot. A cumulative look at the data is provided in the tandem plot in Figure F-11.

## *OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS*

### Operating Pressure Gradient (Figure F-8)

- Remained below 0.7 psi/ft
  - Lower value than the break pressure gradient in the step rate plot

### Hall Plot and Derivative (Figure F-9)

- Used an average reservoir pressure of 2800 psi
- Indicated negative slope breaks
  - Negative slope breaks suggest injection enhancement or fracturing
- Hall derivative separates below the Hall integral function at each of the slope breaks
  - Representative of a fracturing response

### Silin Slope Plot (Figure F-10)

- Slope of the straight line trend on the Silin slope plot estimated an average reservoir pressure of 3324 psi
  - Higher than some of the calculated injecting BHP values
  - Value higher than the 2800 psi value used for the Hall integral calculation

### Tandem Plots

- Hall integral and cumulative earthquake events were plotted on the same graph with a common x axis (Figure F-11)
  - Limited cumulative earthquake count
  - Showed fracture signature prior to earthquake count
- Seismicity timeline (Figure F-2)
  - No correlation in events observed

A linear plot of the step rate test data was plotted and shown in Figure F-12. The linear plot is the final injection pressure at the end of each rate step versus the injection rate for that step. EPA was unable to obtain any electronic data of the step rate test so no log-log plot of each individual injectivity test could be analyzed. The well went on a vacuum following the first rate step. Pressures increased to nearly 2000 psi after positive pressures were reestablished during the 5<sup>th</sup> rate step.

### Step Rate Test (Figure F-12)

- Linear plot indicated a slope break between the 6<sup>th</sup> and 7<sup>th</sup> rate steps of 4 and 5 barrels per minute
  - Suggesting a fracture extension surface pressure of roughly 1700 psi
    - Value would suggest a fracture gradient on the order of 0.7 psi/foot

Although the Hall plot showed several slope breaks, the calculated operating gradient showed operating gradients below 0.7 psi/foot, below the fracture extension gradient indicated by the step rate test linear plot.

#### *ACTIONS TAKEN BY UIC REGULATORY AGENCY IN BRAXTON COUNTY, WV AREA*

In response to the seismic activity starting in April 2010, the West Virginia Department of Environmental Protection Office of Oil and Gas (WVDEP) reduced the injection rate in the Elk Valley Land Corp SWD. Because of the January 2012 event, the WVDEP restricted both the volume and rate into the well versus just the rate in an effort to further minimize seismic events.

#### *REFERENCES*

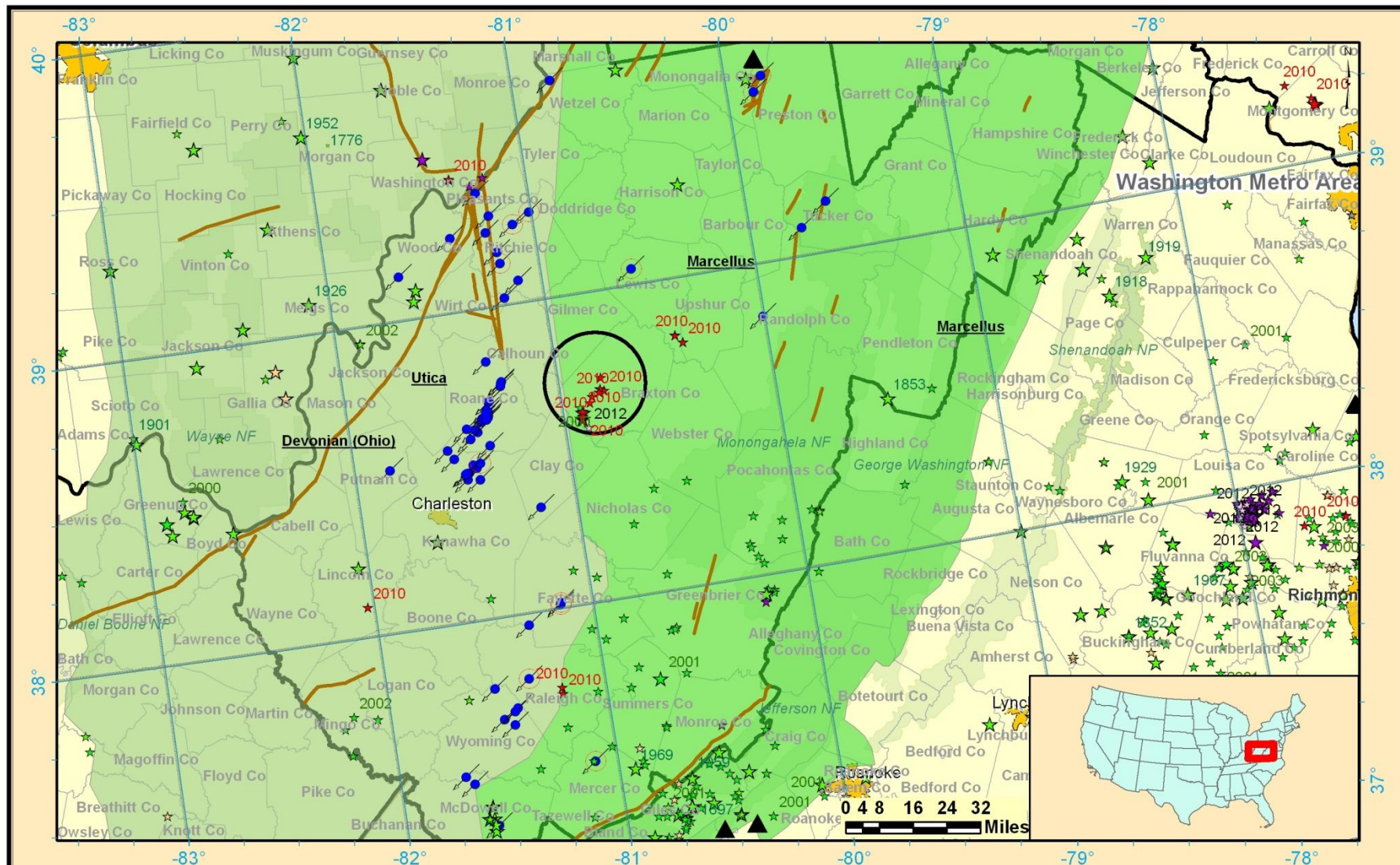
ANSS: <<http://quake.geo.berkeley.edu/cnss/>>

Avary, K. L., 2011, Overview of gas and oil resources in West Virginia, West Virginia Geological & Economic Survey.

Boyce, M. L., and Carr, T. R., 2009, Lithostratigraphy and petrophysics of the Devonian Marcellus interval in West Virginia and southwestern Pennsylvania: Morgantown, West Virginia University, p. 25.



# FIGURE F-1: WEST VIRGINIA LOCATION MAP



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

## Magnitude

- No Magnitude
- ★ 0 - 3
- ★ 3.1 - 5
- ★ 5.1 - 6

## Earthquake Year

- |      |       |
|------|-------|
| 2012 | 2009  |
| 2011 | 2008  |
| 2010 | <2008 |

## Seismometers

- ▲ <all other values>
- ▲ Ended
- ▲ Operating
- Wells of Interest

## Wells

- Injection/Disposal Well
- Commercial Inj

## Horizon

- Structure Contours
- Faults

## Shale Plays

- Trenton
- Marcellus

- Search area

## Albers Projection

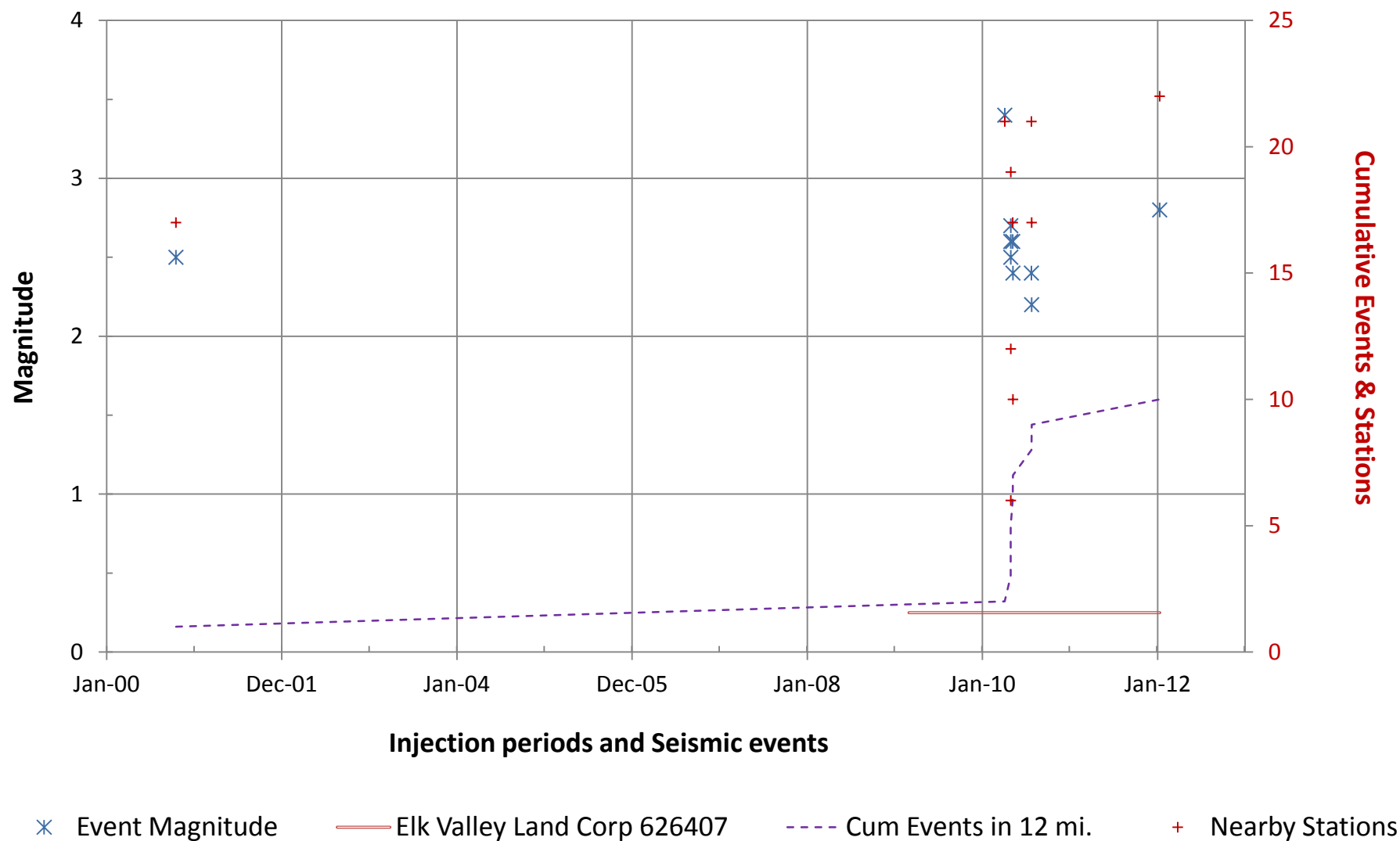
Central Meridian: -96  
1st Std Parallel: 20  
2nd Std Parallel: 60  
Latitude of Origin: 40

Compiled by:  
Nancy Dorsey, EPA R6

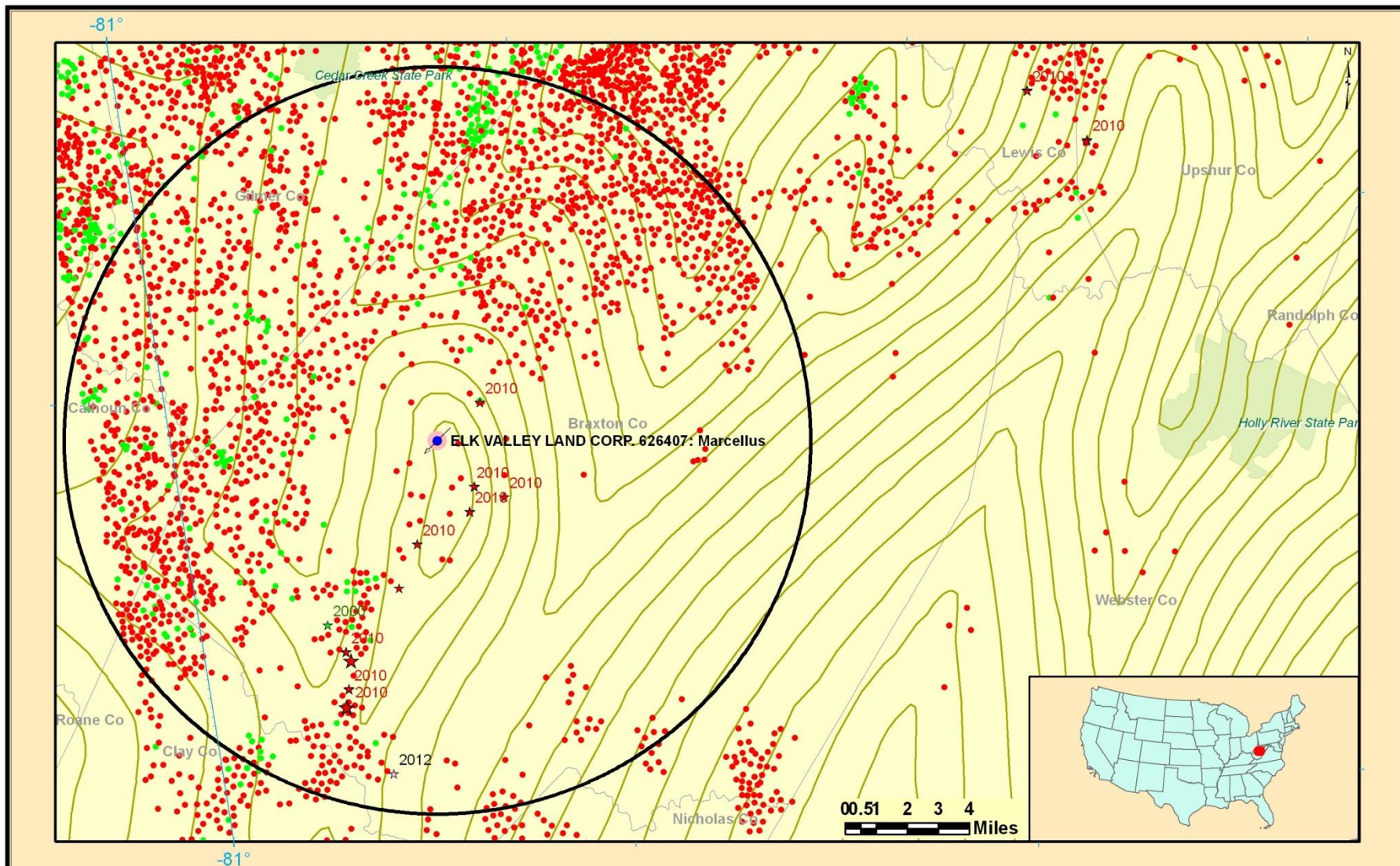


FIGURE F-2: BRAXTON AREA TIMELINE OF EVENTS

Elk Valley Land Corp 626407 Seismicity



# FIGURE F-3: BRAXTON AREA SEISMICITY MAP



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

## Magnitude

- No Magnitude
- ★ 0 - 3
- ★ 3.1 - 5
- ★ 5.1 - 6

## Earthquake Year

- |      |       |
|------|-------|
| 2012 | 2009  |
| 2011 | 2008  |
| 2010 | <2008 |

## Seismometers

- △ <all other values>
- △ Ended
- ▲ Operating
- Wells of Interest

## Wells

- Injection/Disposal Well
- Gas Well
- Oil Well
- Commercial Inj

## Horizon: Onondaga

- Structure Contours
- Faults
- Search area

## Albers Projection

Central Meridian: -96  
1st Std Parallel: 20  
2nd Std Parallel: 60  
Latitude of Origin: 40

Compiled by:  
Nancy Dorsey, EPA R6

FIGURE F-4: WEST VIRGINIA NOMENCLATURE (AVARY, 2011)

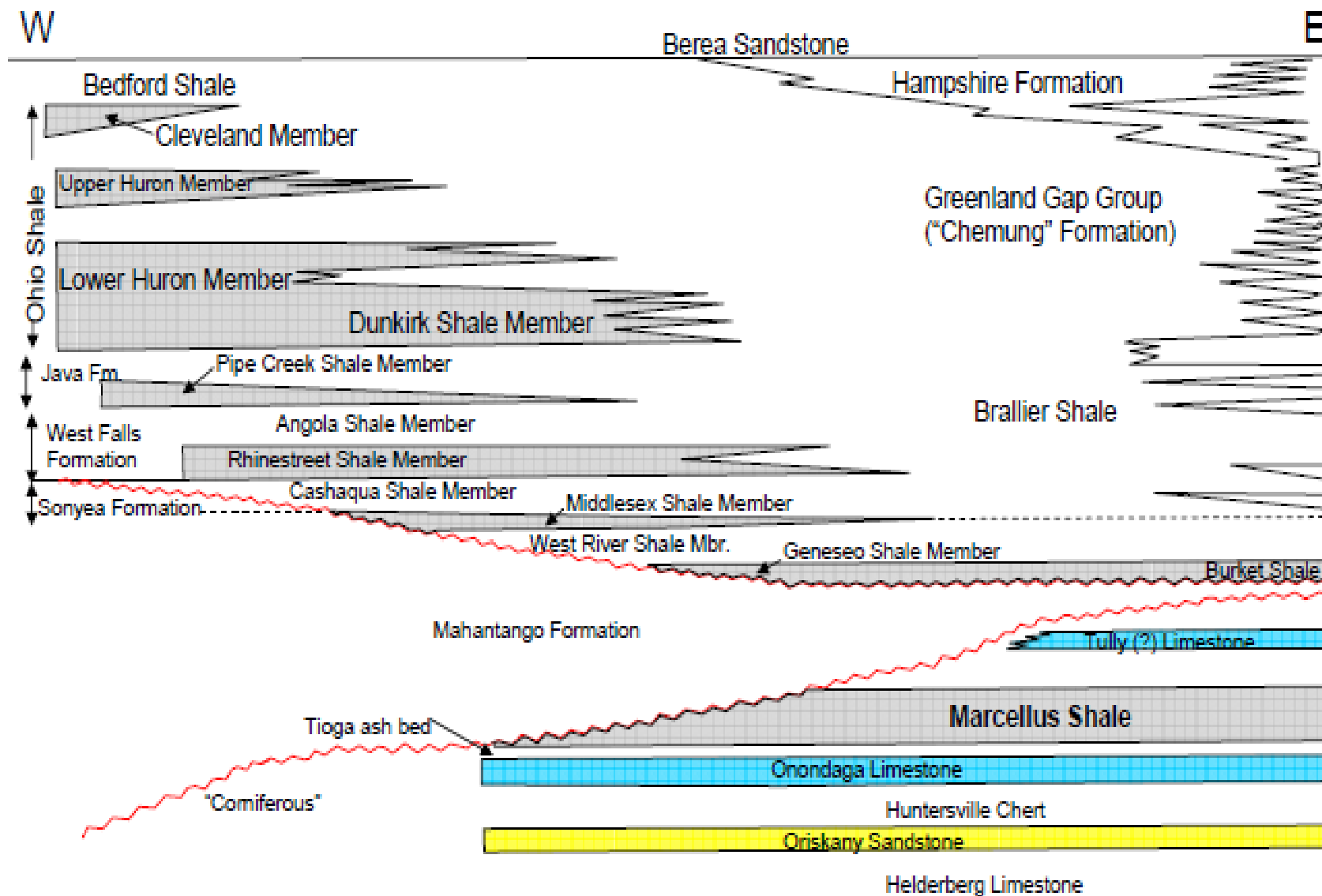


FIGURE F-5: WEST VIRGINIA STRATIGRAPHIC COLUMN  
UNPUBLISHED INFORMATION FROM WVGES (2011)

| Geologic Age  |               |        | Western WV   | Eastern WV  | Drillers' Terminology  |
|---------------|---------------|--------|--|---|--|
| PALEOZOIC ERA | Eocene        |        | Igneous Rock   |   |  |
|               | Jurassic      |        | Igneous Rock   |   |  |
|               | PERMIAN       |        | Dunkard Group  |   |  |
|               |               | Late   | Monongahela Fm.  |   |  |
|               |               | Middle | Conemaugh Group  |   |  |
|               | PENNSYLVANIAN |        | Allegheny Fm.  |   |  |
|               |               | Early  | Pottsville Group   | Kanawha Fm.<br>New River Fm.<br>Pocahontas Fm.                            |  |
|               | MISSISSIPPIAN | Late   | Mauch Chunk Group  | Bluestone Fm.<br>Hinton Fm.<br>Bluefield Fm.                              | Pride, Princeton, Ravencroft, Avis, Manton, Little Lims, Pencil Cave, Blue Monday  |
|               |               | Middle | Greenbrier Group   |   | Big Lims, Keener, Big Injun  |
|               |               | Early  | Price Fm.  |   | Big Injun, McCrady, Squaw, Weir, Sunbury   |
|               | DEVONIAN      | Late   | Berea Ss.  |   |  |
|               |               |        | Ohio Sh. { Cleveland Sh.<br>Chagrin Sh.<br>Huron Sh.<br>Java Fm. } | Hampshire Fm.   | Gantz, 50', 30', Gordon, Gordon Stray, 4", 5", Bayard, Elizabeth, Warren, Speechley, Balltown, Bradford, Riley, Bendon, Alexander, Elk, Haverly, Fox, Sycamore |
|               |               |        | West Falls Fm. { Angola Sh.<br>Rhine Street Sh. }                  | Greenland Gap Group { Foreknobs Fm.<br>Scherr Fm. }                       |  |
|               |               |        | Sonyea Group<br>Genesee Group<br>Berkett Sh.                       | Brallier Fm.  |  |
|               |               | Middle | Harrell Sh.<br>Tully Ls.<br>Mahantango Fm.<br>Marcellus Sh.        | Millboro Sh.  |  |
|               |               |        | Tioga Ash  |   |  |
|               |               |        | Onondaga Ls. { }<br>Huntersville Cht. { }                          | Huntersville Cht. { }<br>Needmore Sh. { }                                 |  |
|               |               | Early  | Oriskany Ss.   | Oriskany Ss.<br>Shriver Chert   |  |
|               |               |        | Helderberg Group   |   |  |
|               |               | Late   | Salina Fm.   | Bass Islands Dol.<br>Tonoloway Fm.<br>Wills Creek Fm.<br>Williamsport Ss. |  |
|               |               |        | Newburg Ss.  |   |  |

|                         |                          |                  |                         |                   |
|-------------------------|--------------------------|------------------|-------------------------|-------------------|
| Igneous/<br>Metamorphic | Coal-bearing<br>interval | Organic<br>shale | Sequestration<br>target | Confining<br>Unit |
|-------------------------|--------------------------|------------------|-------------------------|-------------------|



# FIGURE F-6: ELK VALLEY LAND CORPORATION SWD WELLBORE SCHEMATIC

## Current Wellbore Schematic

626407  
ELK VALLEY LAND CORP 1 SWD

RECEIVED  
SOURCE WATER  
PROTECTION BRANCH  
11 OCT 12 AM 10:23  
6WQ-S

District: EASTERN CENTRAL  
Field Office: JANE LEW  
County: BRAXTON  
State: WEST VIRGINIA  
Elevation: GL 1,065.00 KB 1,065.00 KB Height: 0.00

Spud Date: 7/14/2007  
API #: 4700702539  
Route:  
PBTD:  
TD: 6,552.0

### Well Config: VERTICAL - Original Hole, 8/27/2010 1 (Disclaimer)

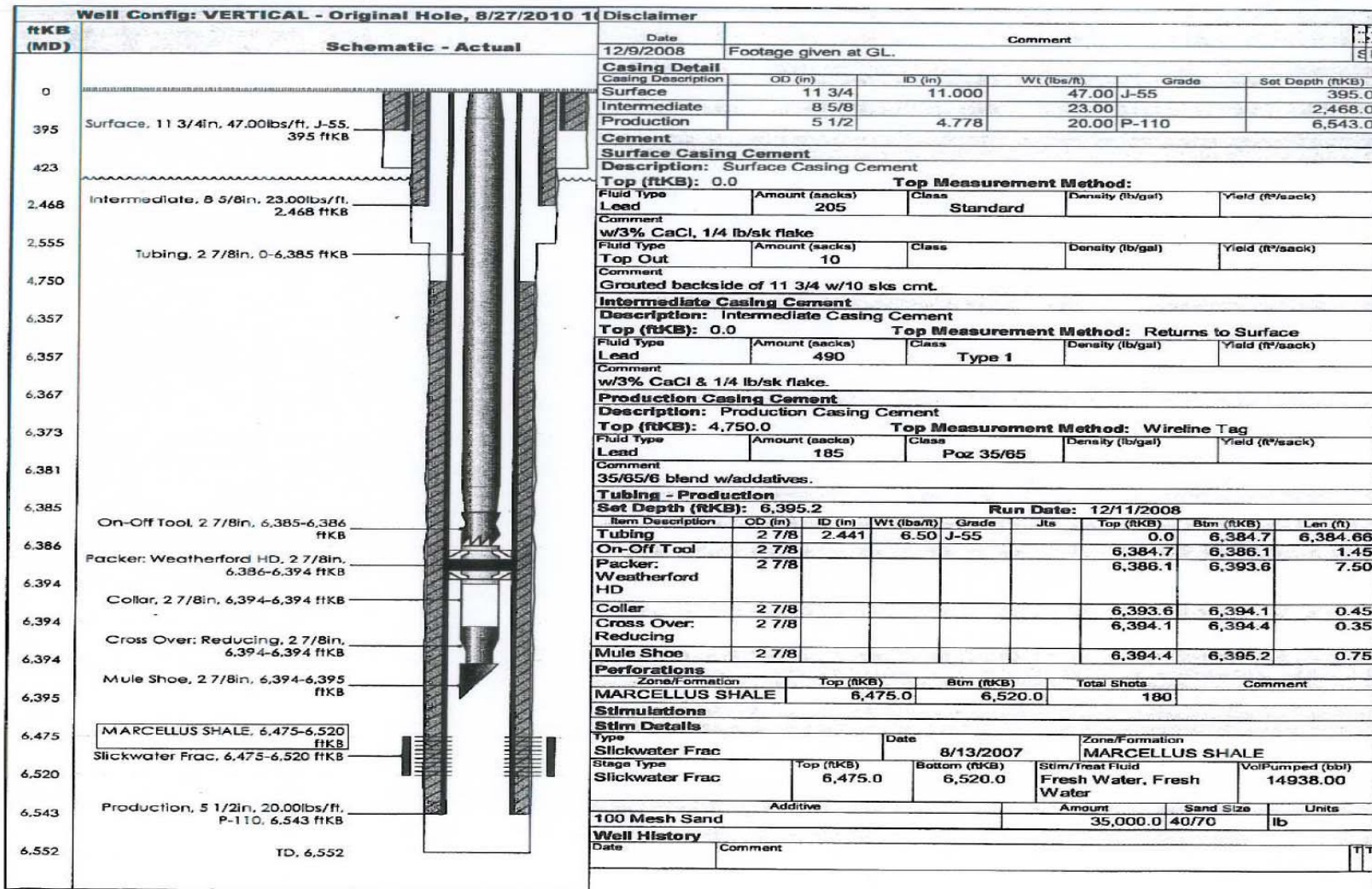


FIGURE F-7: ELK VALLEY LAND CORPORATION SWD OPERATIONAL DATA OVERVIEW PLOT

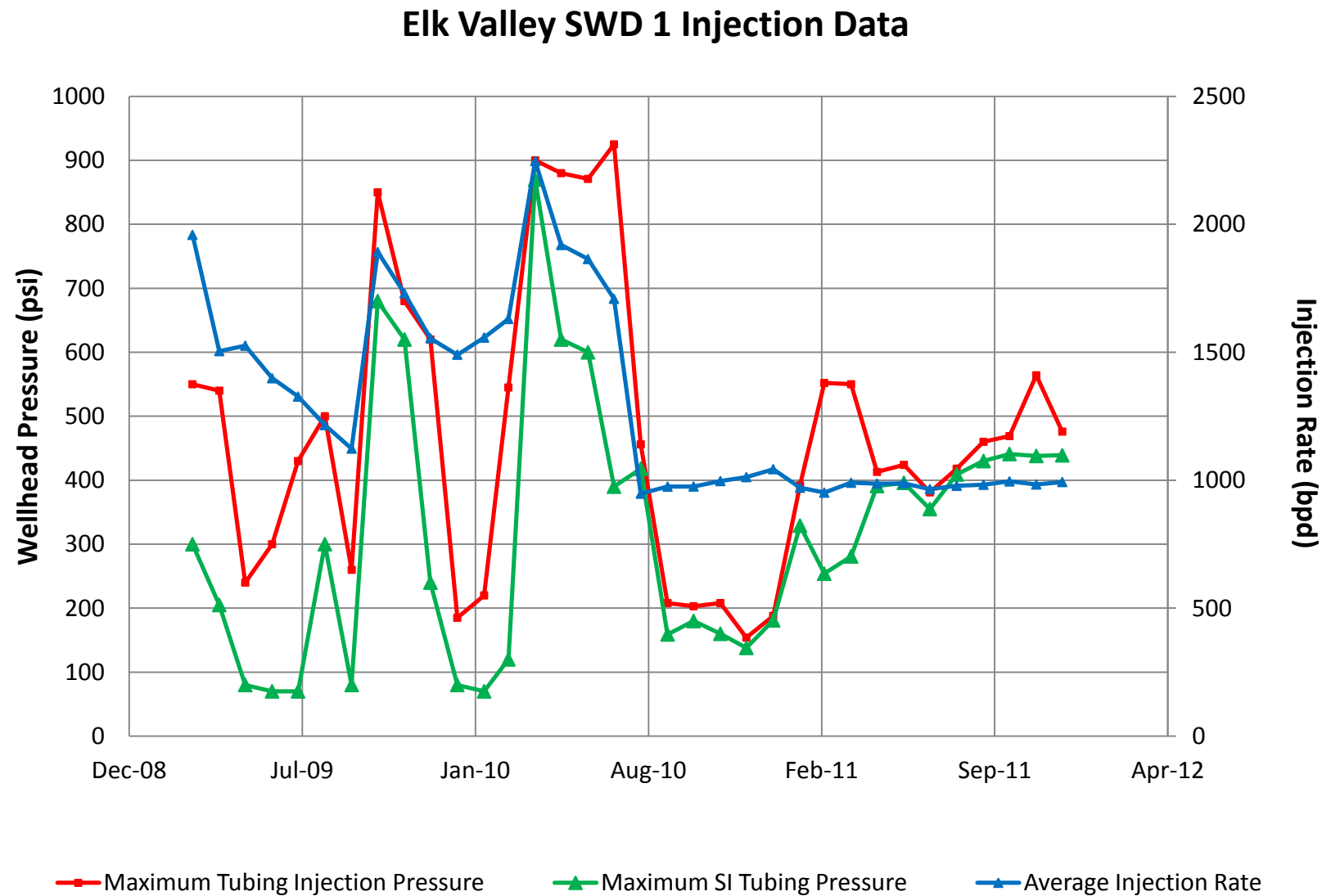


FIGURE F-8: ELK VALLEY LAND CORPORATION SWD OPERATIONAL PRESSURE GRADIENT PLOT

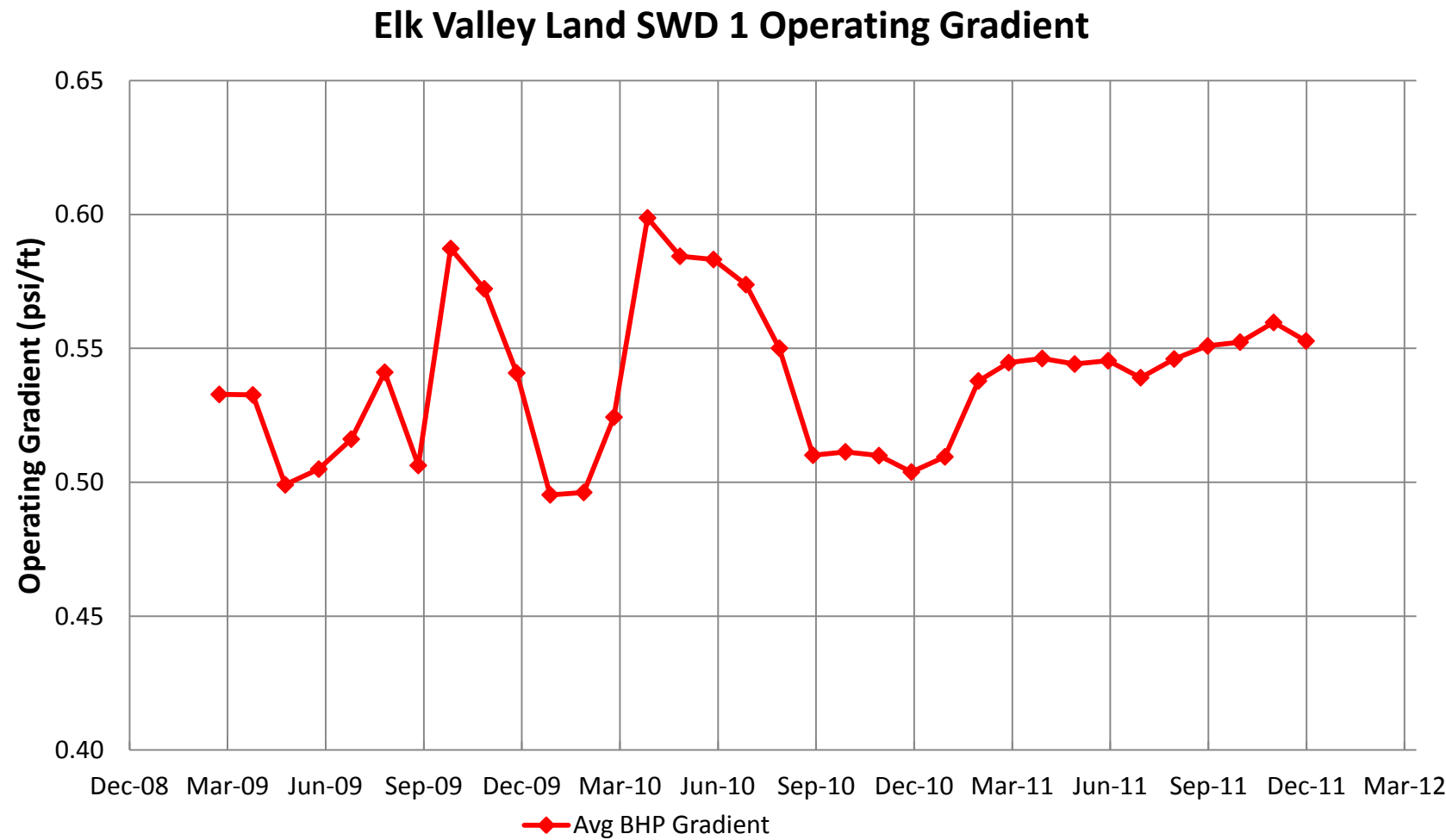


FIGURE F-9: ELK VALLEY LAND CORPORATION SWD HALL INTEGRAL AND DERIVATIVE PLOT

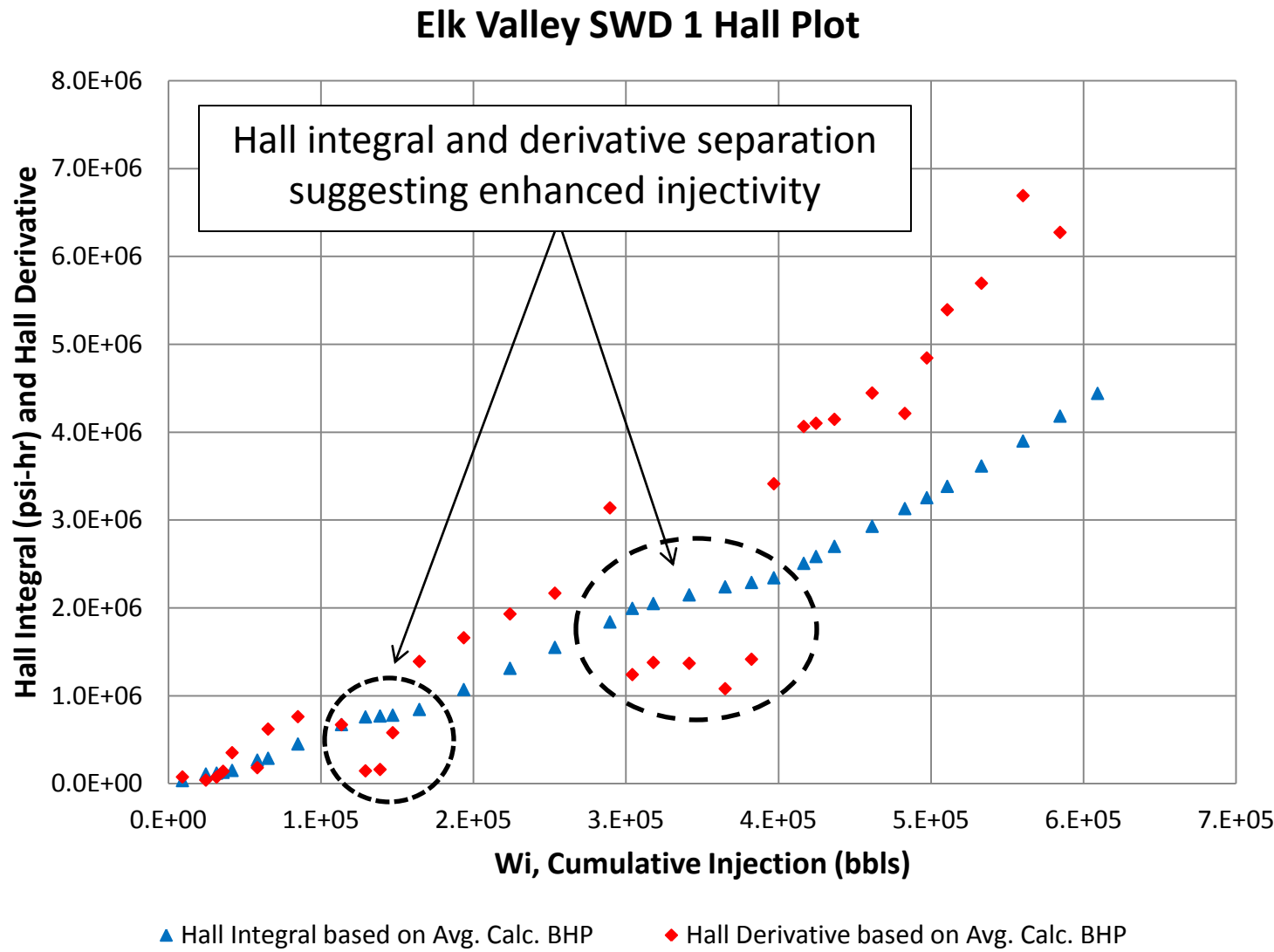




FIGURE F-10: ELK VALLEY LAND CORPORATION SWD SILIN SLOPE PLOT

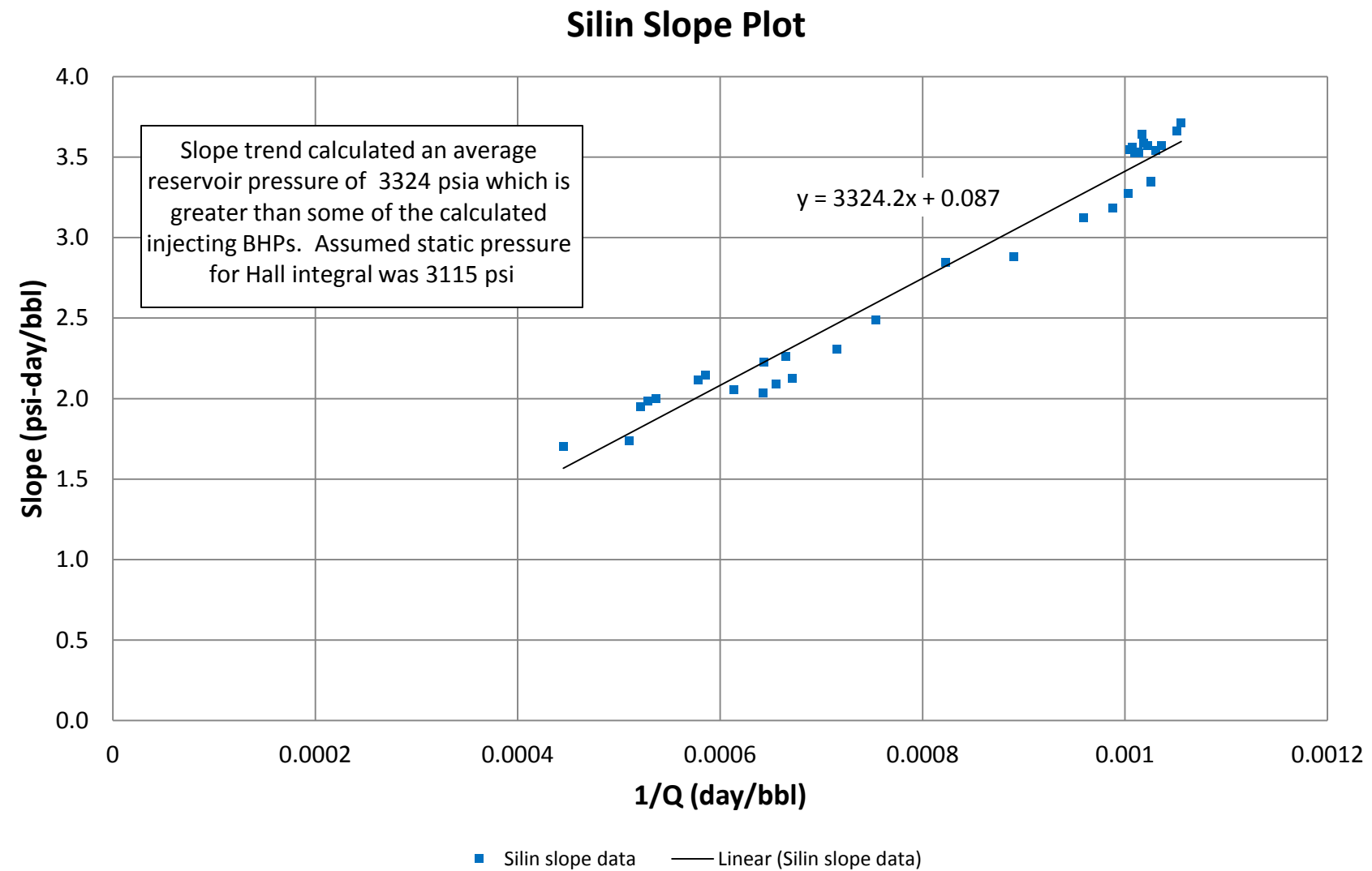


FIGURE F-11: ELK VALLEY LAND CORPORATION SWD TANDEM PLOT

Elk Valley SWD 1 Hall and Cumulative Earthquake Plot

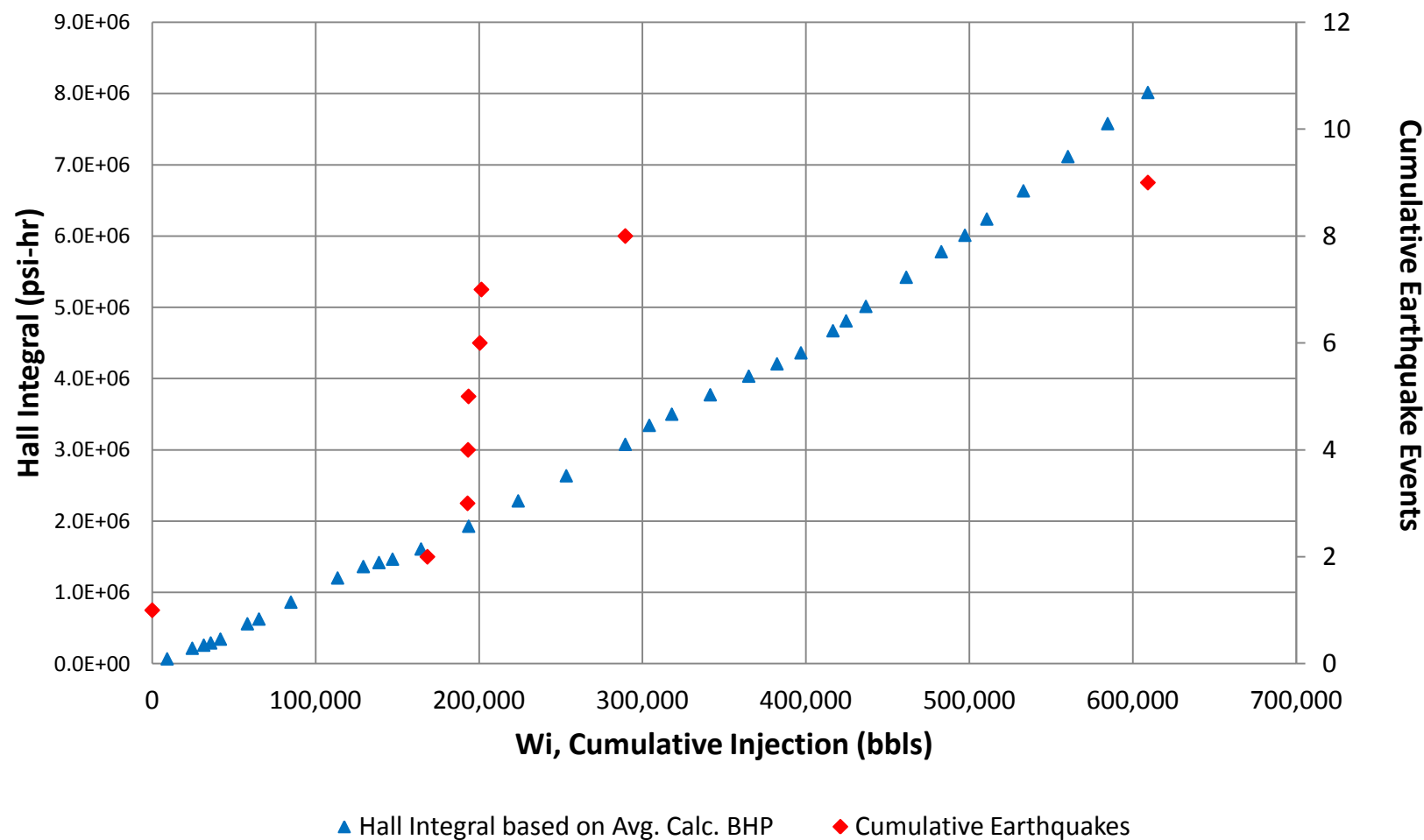
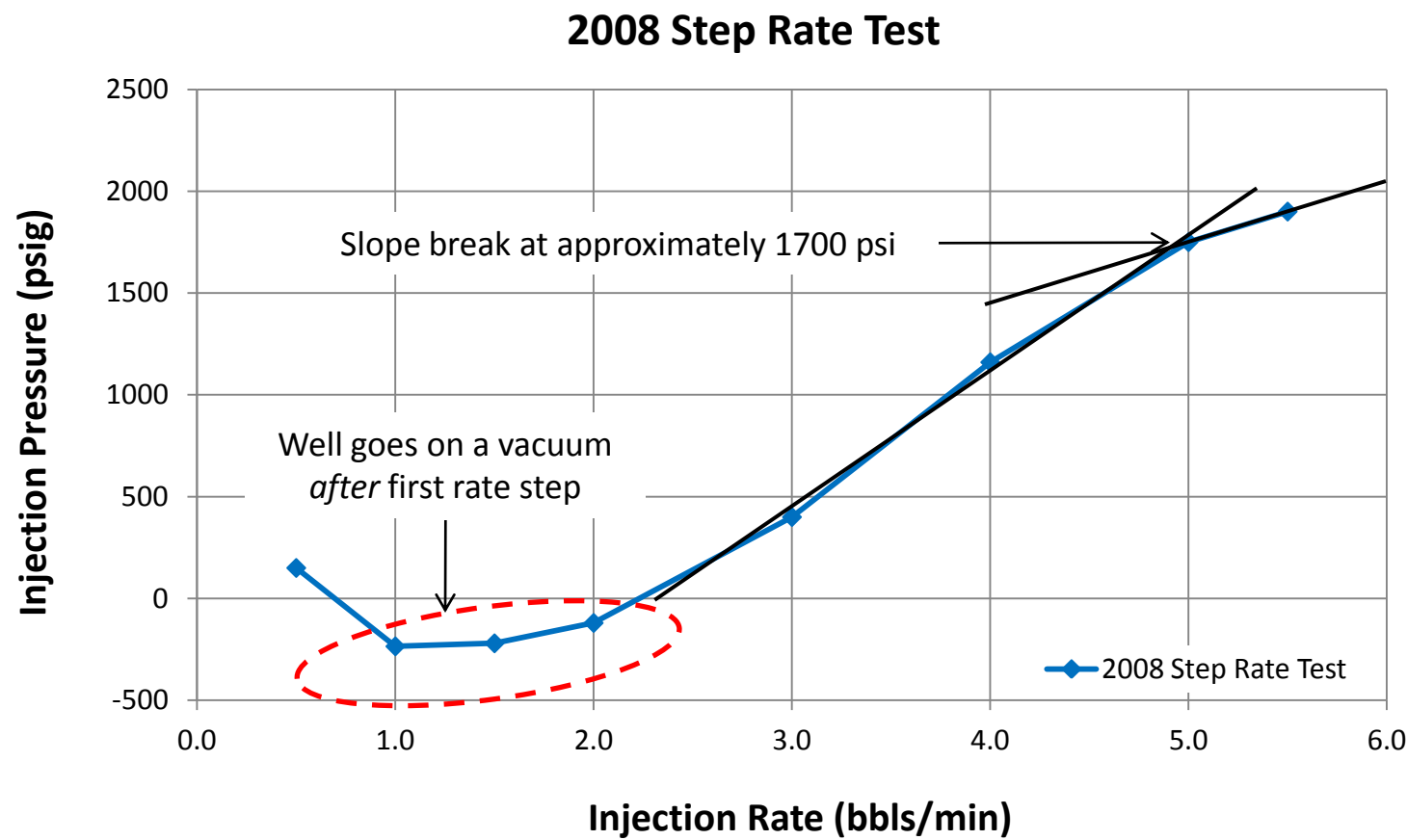


FIGURE F-12: ELK VALLEY LAND CORPORATION SWD STEP RATE TEST



## APPENDIX G: YOUNGSTOWN, OHIO CASE STUDY

|  |     |
|--|-----|
| Background .....   | G-1 |
| History of Seismicity.....   | G-1 |
| Geologic Setting .....   | G-1 |
| Vicinity Disposal Wells .....  | G-2 |
| Data Collected .....   | G-2 |
| Data Reviewed .....  | G-3 |
| Operational Analysis Plots and Observations.....                         | G-3 |
| Actions taken by UIC regulatory agency in the Youngstown, Ohio area..... | G-4 |
| References .....   | G-5 |

### BACKGROUND

On March 17, 2011, a series of low magnitude earthquakes began in Mahoning County in and around Youngstown, Ohio, (Figure G-1). A nearby commercial Class II disposal well, Northstar 1, was shut in by the Ohio Department of Natural Resources (ODNR) following a 4.3 magnitude earthquake on December 31, 2011. According to the *Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio Area* published in March 2012 by the ODNR, data suggests seismicity was related to Class II disposal. The Northstar 1 was drilled 200 feet into the Precambrian basement rock. The ODNR report also suggests that pressure from disposal activities may have communicated with a stressed fault located in the Precambrian basement rock.

### HISTORY OF SEISMICITY

Historically, there had been no prior seismicity in the area, based on a search of the six seismicity databases, (ANSS, SRA, NCEER, USHIS, CERl and PDE). Table G-1 is based on the ANSS catalog and the Ohio Seismic Network and summarizes events occurring within a six mile radius of the North Star 1 case study well. A timeline of events is shown on Figure G-2. A zoomed map area of the disposal well and earthquake activity is included on Figure G-3.

TABLE G-1: YOUNGSTOWN AREA SEISMICITY THROUGH 1/31/2012

| Year | Starting Date | Number of Events | Min. | Avg. | Max. | Ending Date |
|------|---------------|------------------|------|------|------|-------------|
| 2011 | 3/17/2011     | 11               | 2.1  | 2.5  | 4.3  | 12/31/2011  |
| 2012 | 1/13/2012     | 1                | 2.1  | 2.1  | 2.1  | 1/13/2012   |

### GEOLOGIC SETTING

Youngstown is located in Mahoning County near the border of Pennsylvania, on the western flank of the Appalachian Basin. Figure G-4, (Baranoski, 2002; ODNR) illustrates the general structure across Ohio with deep Precambrian structures overlain by Paleozoic beds thickening

1 to the east into the Appalachian Basin. Figure G-5, (ODNR, 2004) shows the stratigraphic  
2 column for eastern Ohio.

3 Oil and gas activity is plentiful in the area, with production from the upper Devonian Berea, and  
4 lower Silurian sandstones. The Cambrian Knox unconformity, rarely penetrated, marks the top  
5 of the injection interval permitted in the Youngstown area. To ensure complete penetration of  
6 the Mount Simon Sandstone, all of the wells were drilled into the Precambrian. ODNR indicates  
7 that the North Star 1 encountered primarily biotite for the first 80 feet of Precambrian before  
8 reaching granite. There were indications of high angle fractures around the contact between  
9 the two rock types.

10 Very little control is available for the basement Precambrian structure, but regional maps based  
11 on well control combined with seismic lines and other control have been compiled, (Baranoski,  
12 2002; ODNR, Pennsylvania Geological Survey, OFGG-05). Comparing the new well information  
13 with the published Precambrian maps supports the lack of additional faulting in the area  
14 around Youngstown.

#### 15 *VICINITY DISPOSAL WELLS*

16 Six North Star disposal wells have been permitted for injection, in the Youngstown area.  
17 According to the ODNR only one has injected, though five have been drilled and completed. All  
18 of them are completed from the Knox into the Precambrian.

19 Injection activities began in the North Star 1 in December 2010 about three months prior to the  
20 start of seismic events. A zoomed map area of the disposal well and earthquake activity in  
21 Mahoning County is included on Figure G-3. Figure G-6 is a wellbore schematic illustrating the  
22 construction and completion information for the North Star 1 summarized below:

23 *North Star 1 (SWIW 10);* UIC Permit 3127; Completed 05/13/2010; Initial injection 12/22/10;  
24 openhole completed interval 8,215'-9,180', top Knox through 200' of Precambrian. Acidized  
25 8/2/2011.

#### 26 *DATA COLLECTED*

27 The ODNR through the Oil and Gas Resources Division collected and provided the WG with the  
28 permitting, operational data, fluid analysis, and step rate test used to evaluate the Northstar 1.  
29 Data provided by the Agency included daily injection volumes, daily hours operation, and  
30 wellhead injection pressures. Permit application and completion data provided tubing  
31 dimensions and depth (3 1/2" at an approximate depth of 8215' with an inner diameter  
32 assumed of 2.875"). The fluid analysis indicated a specific gravity of 1.03. Two increases in the

1 maximum allowable surface pressure were authorized by ODNR based on the specific gravity of  
2 the injectate.

### 3 *DATA REVIEWED*

4 The available operational data was reviewed. The operating surface pressure was based on the  
5 final daily injection pressure value reported. Surface pressures were converted to bottomhole  
6 pressures (BHP) at 8215 feet. To determine friction pressure, the Hazen-Williams friction loss  
7 correlation with a friction factor, C, of 140 for coated tubing was used. BHPs were calculated by  
8 adding the measured surface pressure and hydrostatic column of fluid and subtracting the  
9 calculated friction pressure loss. A brine specific gravity of 1.03 was used based on the fluid  
10 analysis provided in the permit application. The hydrostatic column of fluid was calculated at  
11 3662 psia. An initial bottomhole pressure of 3803 psi was used based on the initial pressure  
12 measured in Northstar 4. Five operating data-related plots (Figures G-7 through G-11) were  
13 prepared including an operational overview data plot, an operating gradient plot, a Hall integral  
14 and derivative plot based on average tubing pressure, Silin slope plot, and a tandem plot. The  
15 June 2010 step rate test conducted to evaluate the injectivity into the well was also reviewed  
16 (Figure G-12).

17 Figure G-7 contains an overview plot of the operational data used in the analysis. Figure G-8 is  
18 a plot of the calculated operating pressure gradient. The monthly hours reported indicated that  
19 the well did not operate continually throughout the month. The Hall integral and derivative  
20 functions were plotted as continuous functions from monthly data using only the hours  
21 operated in month for calculation of the functions. For the Hall integral calculations, a static  
22 pressure of 3803 psia was assumed, based on the static bottomhole pressure measurement in  
23 Northstar 4. Figure G-9 is a plot of the Hall integral and derivative trend for the disposal well  
24 and Figure G-10 contains the Silin slope plot. A cumulative look at the data is provided in the  
25 tandem plot in Figure G-11. The step rate test is illustrated in Figure G-12.

### 26 *OPERATIONAL ANALYSIS PLOTS AND OBSERVATIONS*

#### 27 Overview Plot (Figure G-7)

- 28 • Higher injection rates followed acid stimulation

#### 29 Operating Pressure Gradient (Figure G-8)

- 30 • Plateau at 0.75 psi/ft bottom hole operating gradient for extended time frame
- 31 ○ 0.75 psi/ft was basis for determining maximum surface pressure limit in permit

#### 32 Hall Plot and Derivative (Figure G-9)

- 33 • Used an average reservoir pressure of 3803 psi
- 34 • Indicated negative slope break

- Negative slope break suggest injection enhancement or more interval accepting fluid
- Hall derivative stays below the Hall integral function after early initial slope break

#### Silin Slope Plot (Figure G-10)

- Slope of the straight line trend on the Silin slope plot estimated an average reservoir pressure of 5349 psi
  - Value much higher than the 3803 psi value used for the Hall integral calculation based on the measure static bottomhole pressure in the Northstar 4

#### Tandem Plot (Figure G-11)

- Hall integral, Hall derivative, and cumulative earthquake events were plotted on the same graph with a common x axis
  - Limited cumulative earthquake count
  - Earthquakes began after initial slope break
- Seismicity timeline (Figure G-2)

#### Step Rate Test (Figure G-12)

- Designed as an injectivity test to evaluate the formation's ability to accept fluid
- Test conducted through 5.5" production casing
- Pressure fluctuations measured during some of the rate steps
- Full range of pressure gauge (10,000 – 15,000 psi) excessive for measured pressure range (1800 psi maximum)
- Unable to determine from the step rate tests report if the pressure was stabilized during each rate step
- Slope breaks
  - Several different straight lines could be drawn suggesting breaks after steps 2, 5, and 6
  - Final slope is nearly flat between steps 7 and 8

#### *ACTIONS TAKEN BY UIC REGULATORY AGENCY IN THE YOUNGSTOWN, OHIO AREA*

Following a 4.3 magnitude earthquake (ANSS) on December 31, 2011, ODNr shut in the Northstar 1 pending further evaluation. The ODNr will prohibit Class II injection into the Precambrian basement rock and has proposed additional standard permit requirements to facilitate better site assessment and collection of more comprehensive well information. The proposed supplemental permit application documentation will include more geologic data, comprehensive well logs, a plan of action should seismicity occur, a step-rate test, a determination of the initial bottomhole pressure, and a series of operational controls: continuous pressure monitoring system, an automatic shut-off system, and an electronic data

1 recording system for tracking fluids. ODNR is also considering purchasing seismometers to  
2 bolster earthquake monitoring capabilities.

### 3 *REFERENCES*

4 ANSS: <<http://quake.geo.berkeley.edu/cnss/>>

5 Baranoski, M.T., 2002, in Structure Contour Map on the Precambrian Unconformity Surface in  
6 Ohio and Related Basement Features, Ohio Department of Natural Resources, Division  
7 of Geological Survey Map PG-23.

8 ODNR, 2004, Ohio Division of Geological Survey, Generalized column of bedrock units in Ohio:  
9 Ohio Department of Natural Resources, Division of Geological Survey, 1 p.  
10 <http://www.dnr.state.oh.us/Portals/10/pdf/stratcol.pdf>

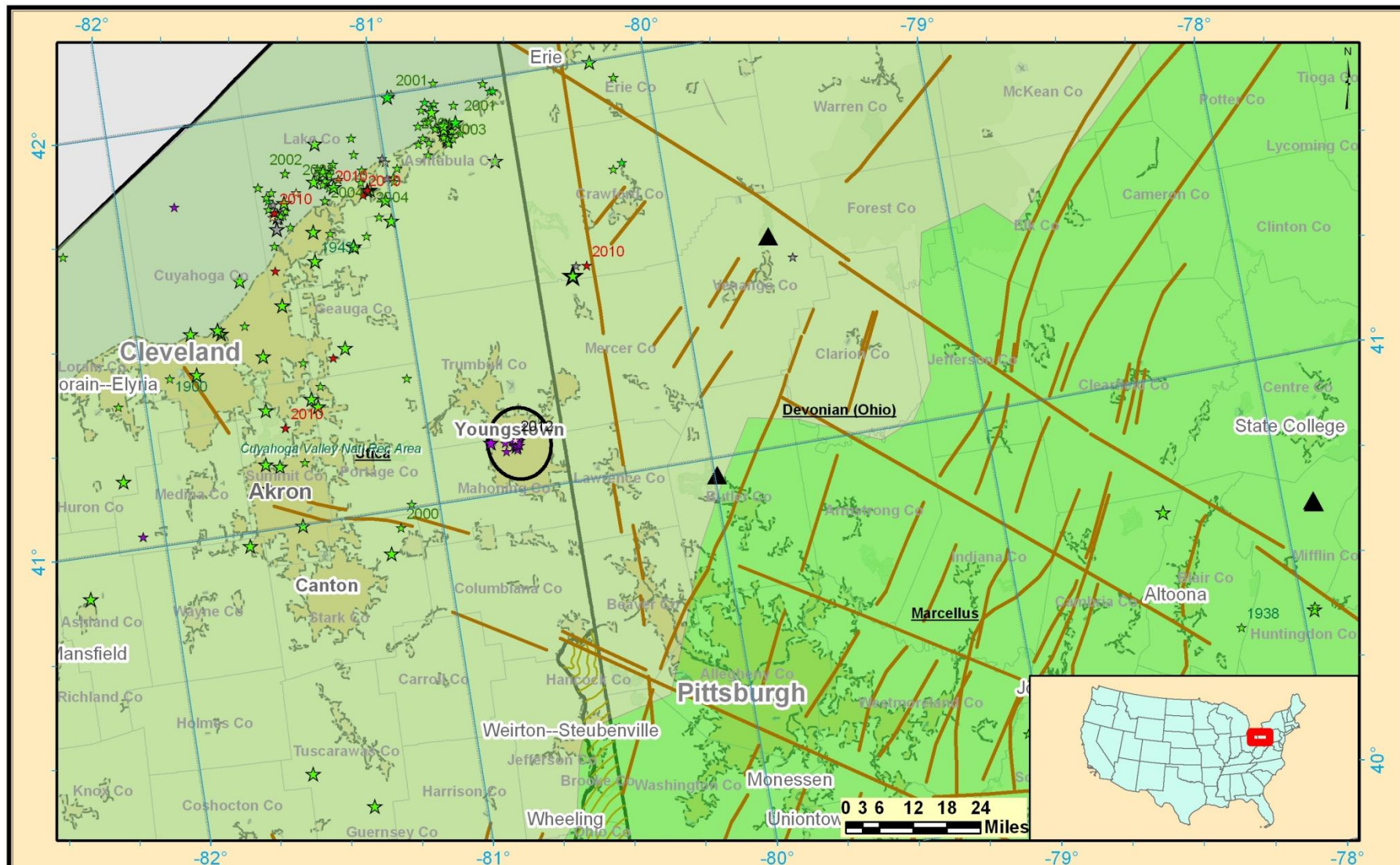
11 ODNR, 2012, Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic  
12 Events in the Youngstown, Ohio Area: Ohio Department of Natural Resources, 24 p. plus  
13 figures.  
14 [http://www.ohiodnr.com/home\\_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-](http://www.ohiodnr.com/home_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx)  
15 [New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx](http://www.ohiodnr.com/home_page/NewsReleases/tabid/18276/EntryId/2711/Ohios-New-Rules-for-Brine-Disposal-Among-Nations-Toughest.aspx).

16 Ohio Seismic Network: <<http://www.ohiodnr.com/geosurvey/default/tabid/8144/Default.aspx>>

17 Pennsylvania Geological Survey, 2005, Alexander, S. S., Cakir, R., Doden, A. G., Gold, D. P., and  
18 Root, S. I. (compilers), Basement depth and related geospatial database for  
19 Pennsylvania: Pennsylvania Geological Survey, 4th ser., Open-File General Geology  
20 Report 05-01.0, [www.dcnr.state.pa.us/topogeo/openfile](http://www.dcnr.state.pa.us/topogeo/openfile).



# FIGURE G-1: OHIO LOCATION MAP



Earthquakes through 01/31/2012

If legend item, does not show in map, it is not in the area.

**Magnitude**

- No Magnitude
- ★ 0 - 3
- ★ 3.1 - 5
- ★ 5.1 - 6

**Earthquake Year**

|      |       |
|------|-------|
| 2012 | 2009  |
| 2011 | 2008  |
| 2010 | <2008 |

**Seismometers**

- △ <all other values>
- △ Ended
- ▲ Operating
- Wells of Interest

**Wells**

- Injection/Disposal Well
- Commercial Inj

**Horizon: Basement Faults**

- Structure Contours
- Faults

**Shale Plays**

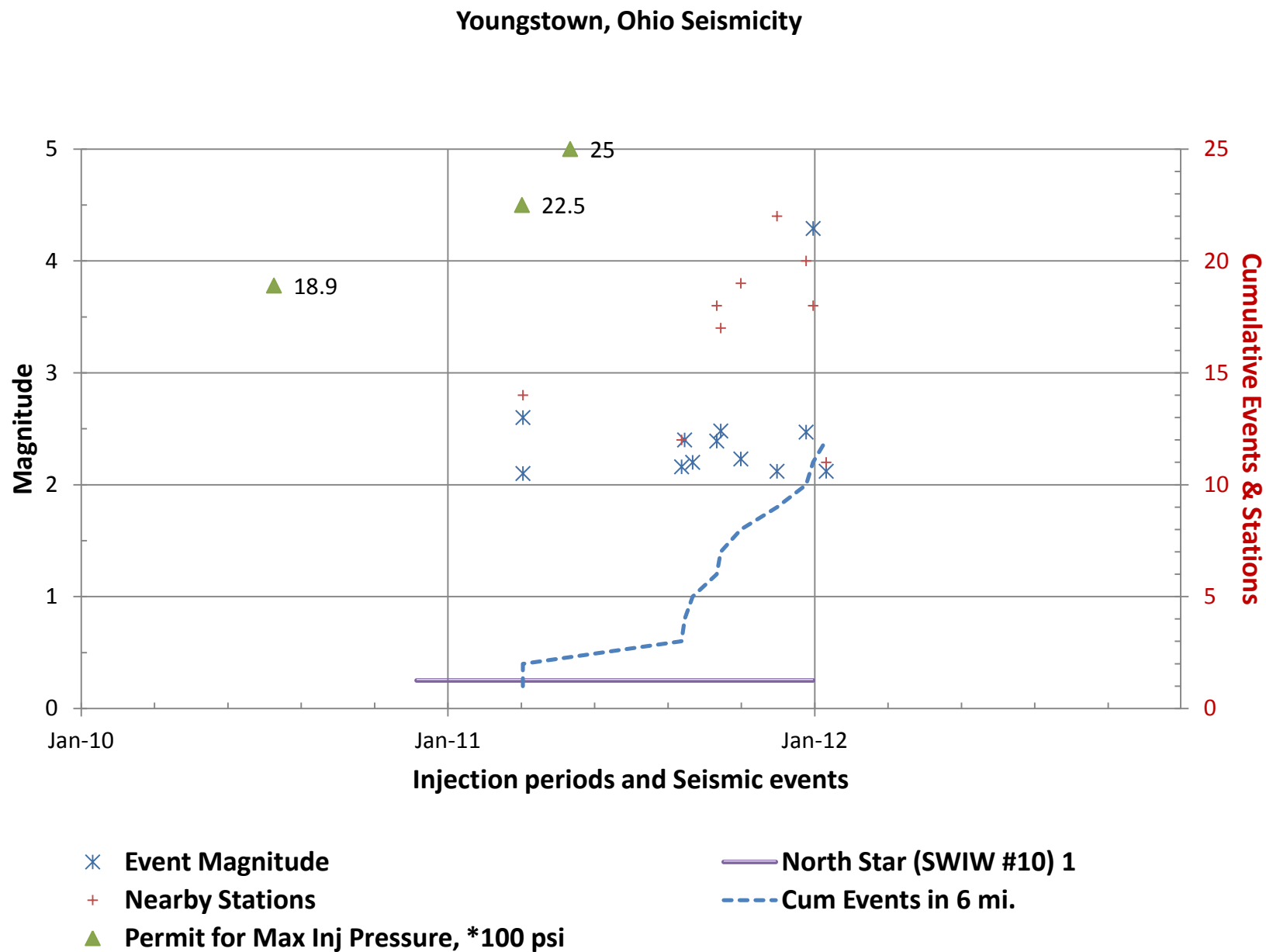
- Trenton
- Marcellus

○ Search area

**Albers Projection**  
 Central Meridian: -96  
 1st Std Parallel: 20  
 2nd Std Parallel: 60  
 Latitude of Origin: 40

Compiled by:  
 Nancy Dorsey, EPA R6

FIGURE G-2: YOUNGSTOWN AREA TIMELINE OF EVENTS



# FIGURE G-3: YOUNGSTOWN AREA SEISMICITY MAP

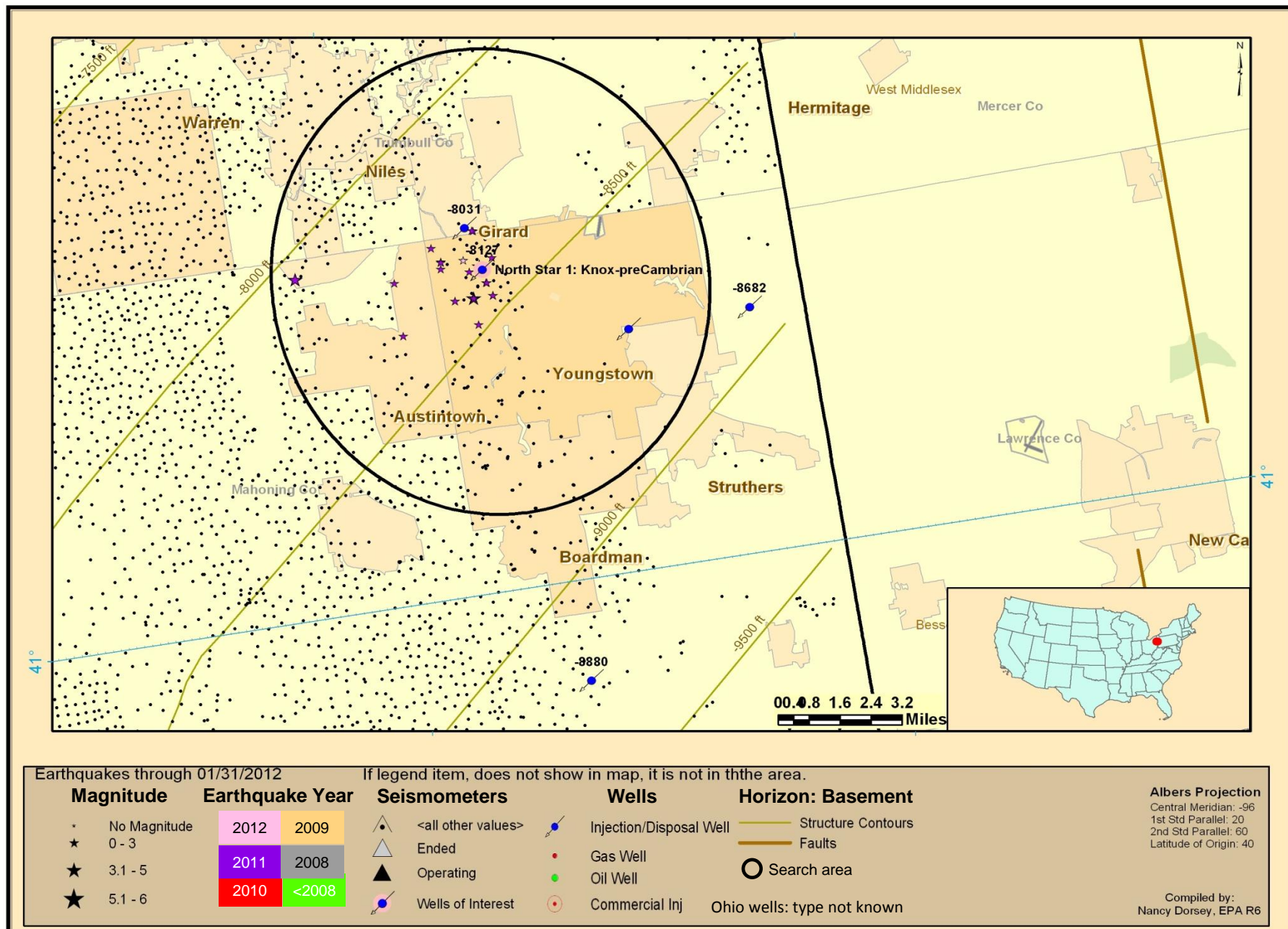
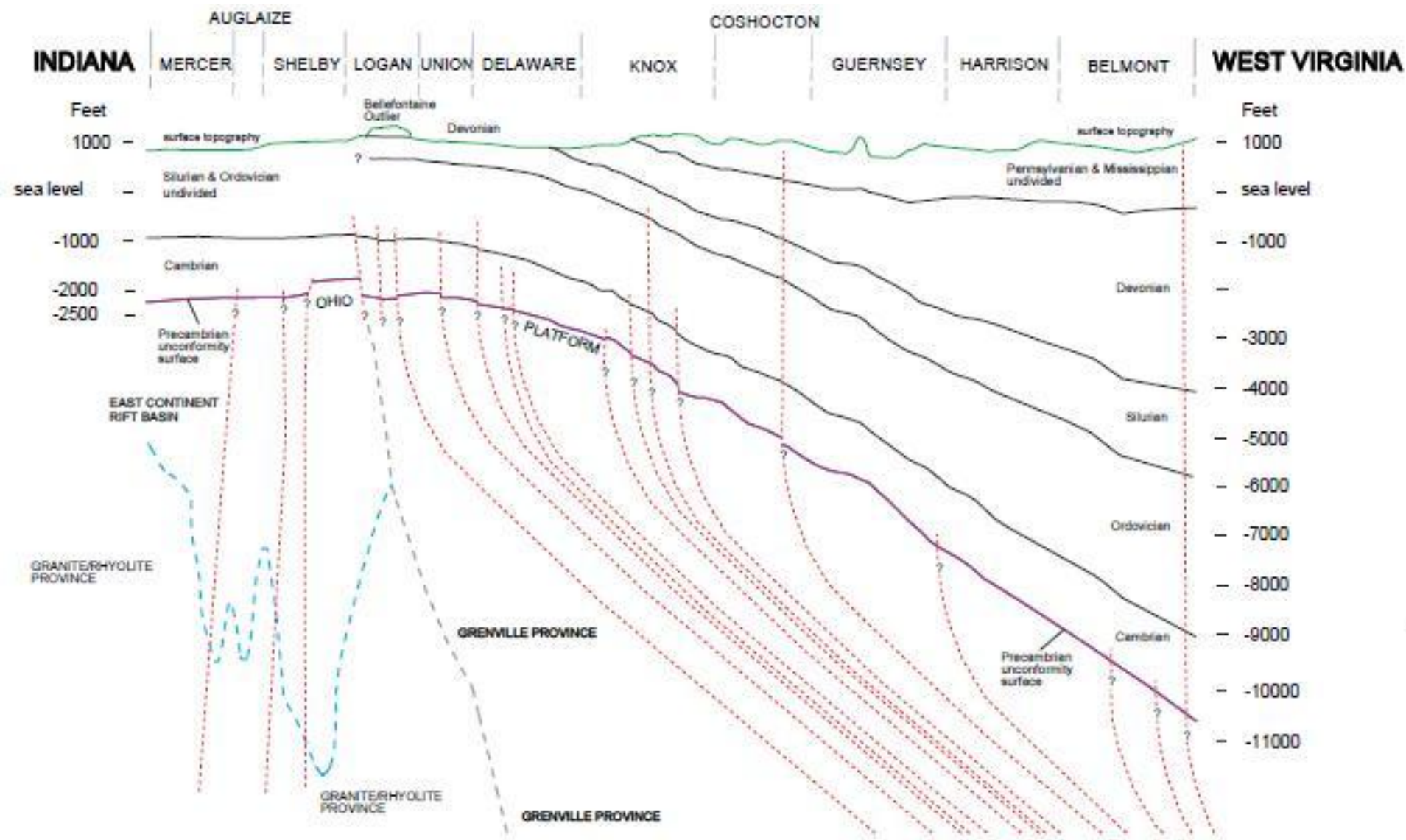




FIGURE G-4: OHIO GENERAL STRUCTURAL CROSS-SECTION  
(BARANOSKI, ODNR PG-23, 2002)



Datum = sea level. Vertical exaggeration = 50X.

Diagram based on interpretation approximately along COCORP OH-1 and OH-2 seismic lines.

FIGURE G-5: OHIO STRATIGRAPHIC COLUMN (ODNR, 2004)

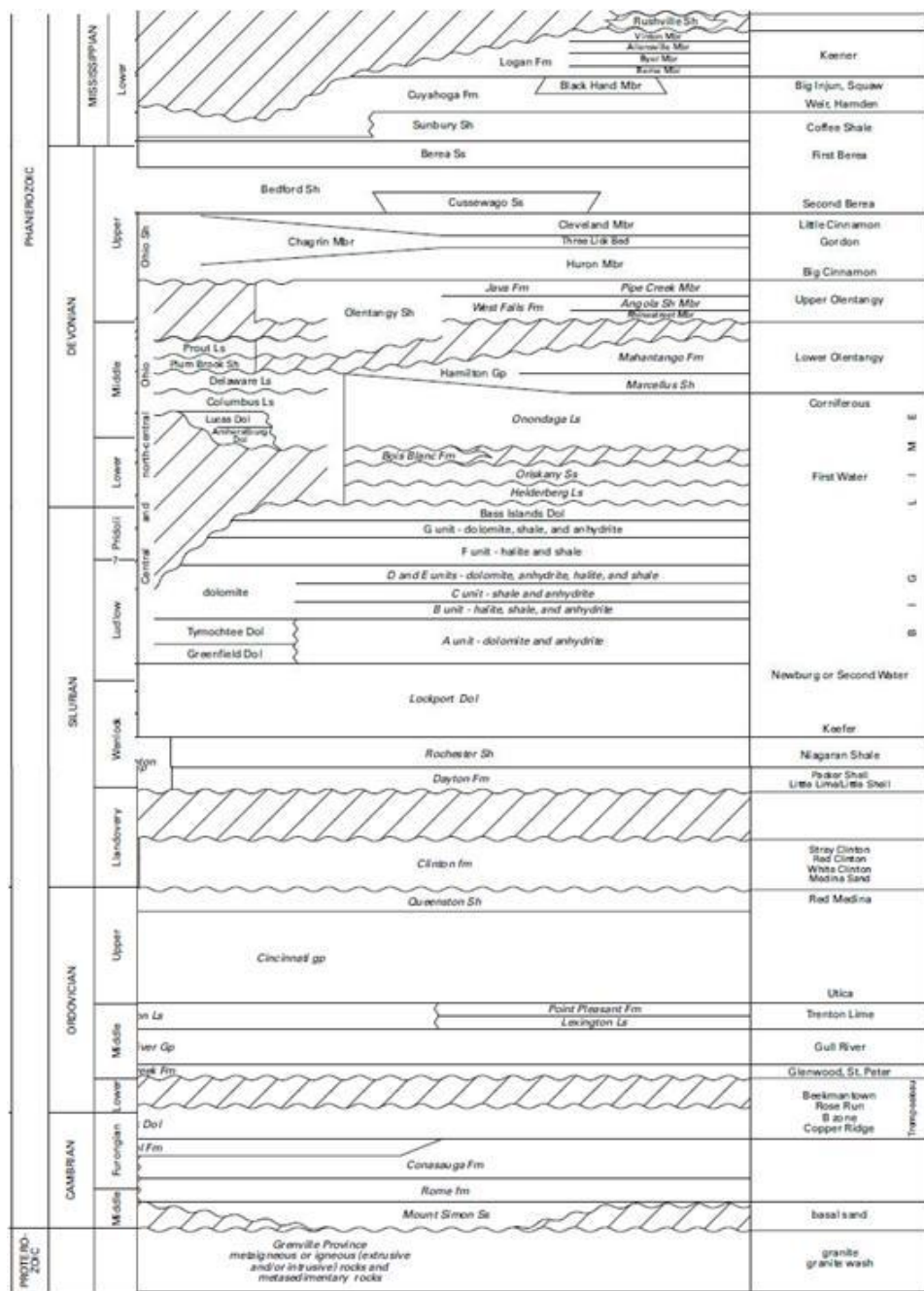


FIGURE G-6: NORTH STAR NO. 1 SWD WELLBORE SCHEMATIC

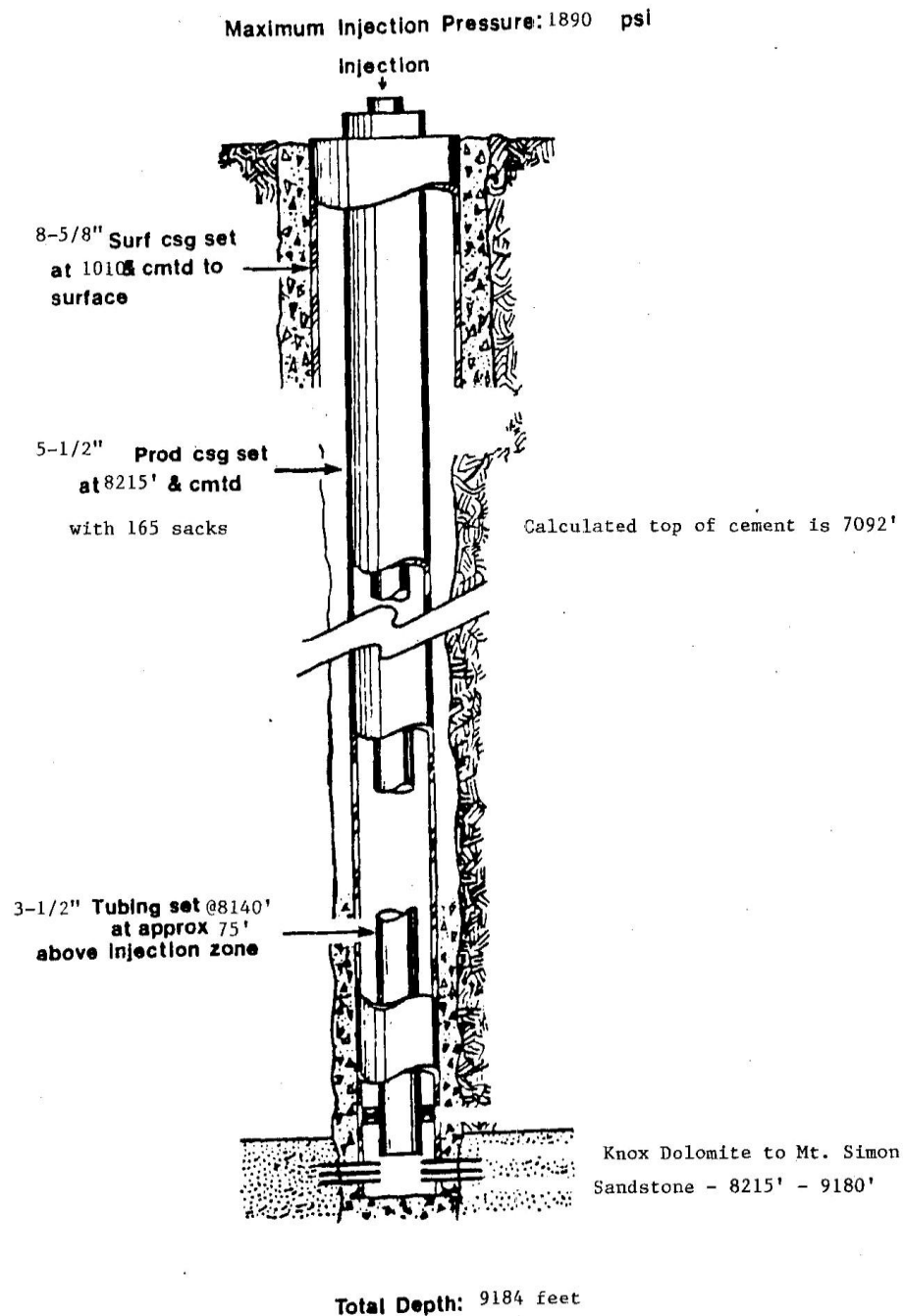


FIGURE G-7: NORTH STAR NO. 1 SWD OPERATIONAL DATA OVERVIEW PLOT

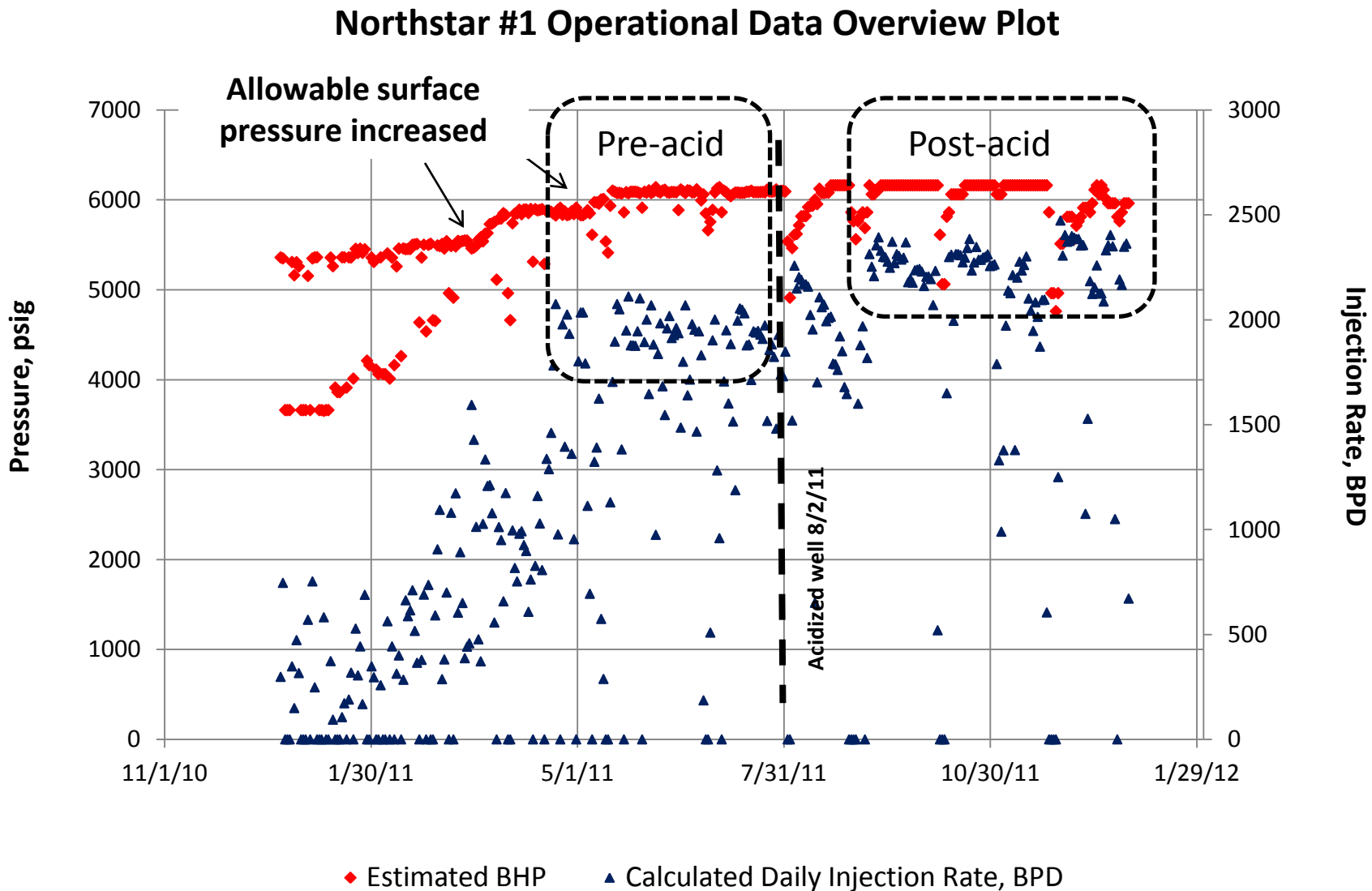


FIGURE G-8: NORTH STAR NO. 1 SWD OPERATIONAL PRESSURE GRADIENT PLOT

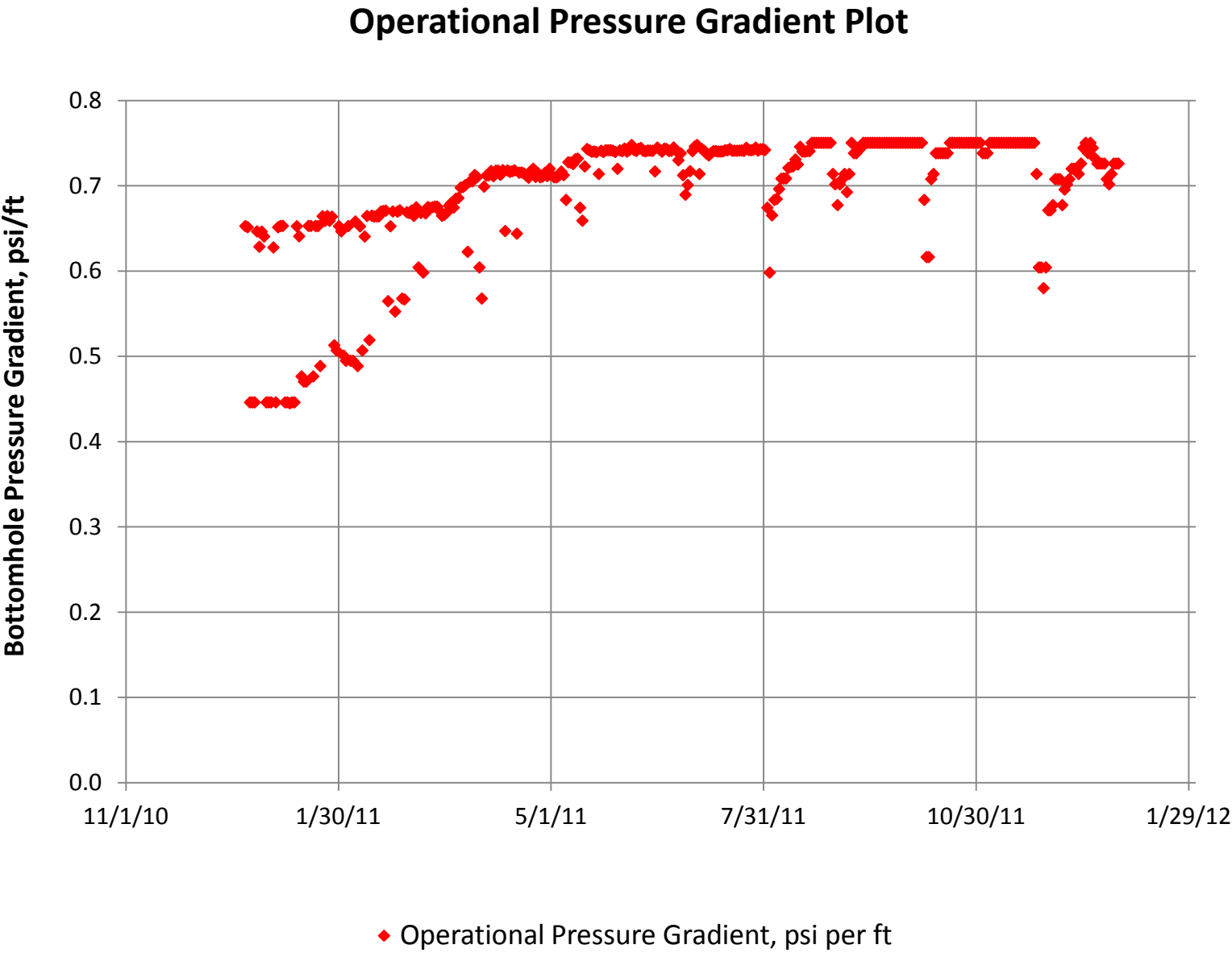




FIGURE G-9: NORTH STAR NO. 1 SWD HALL INTEGRAL AND DERIVATIVE PLOT

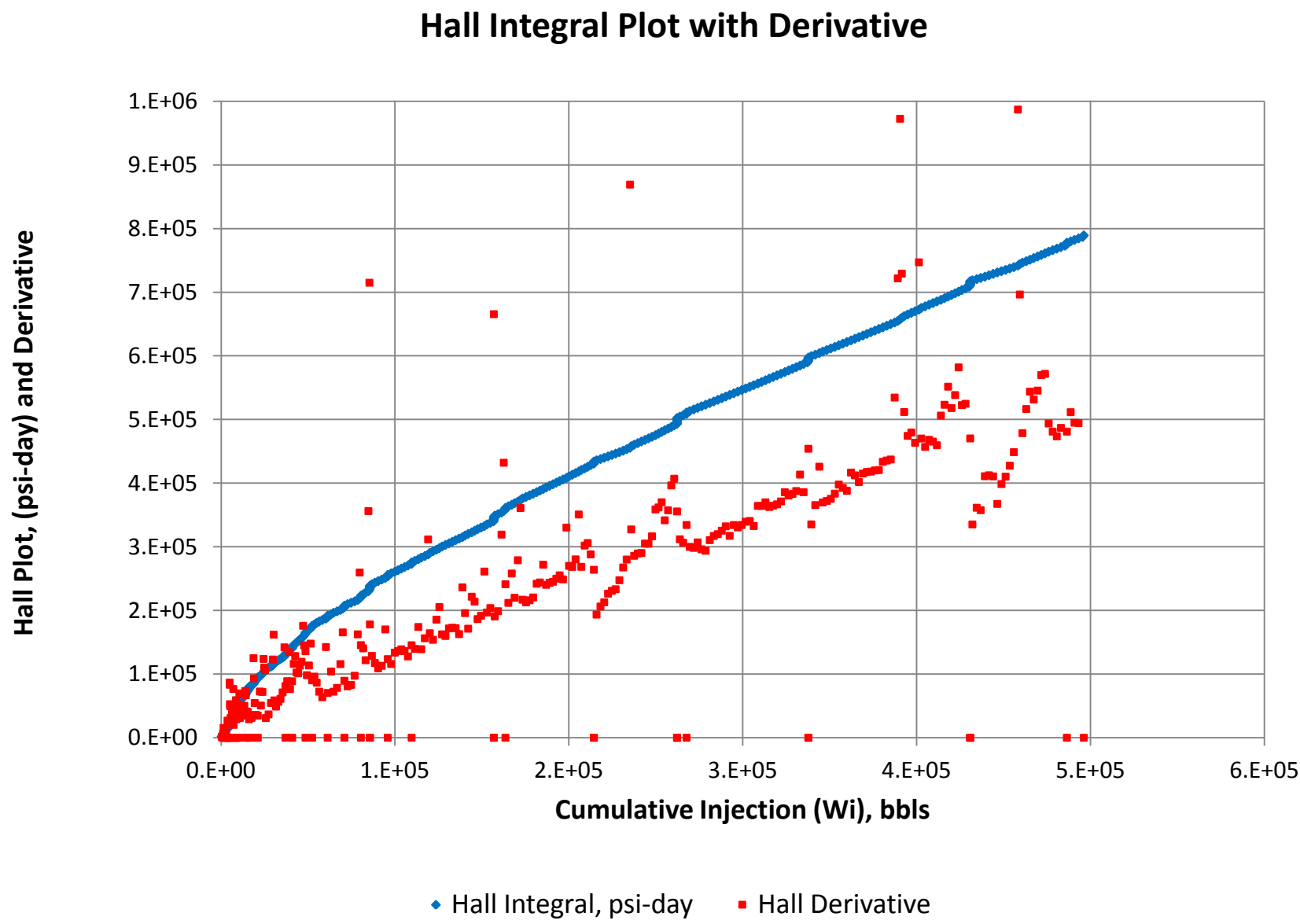


FIGURE G-10: NORTH STAR NO. 1 SWD SILIN SLOPE PLOT

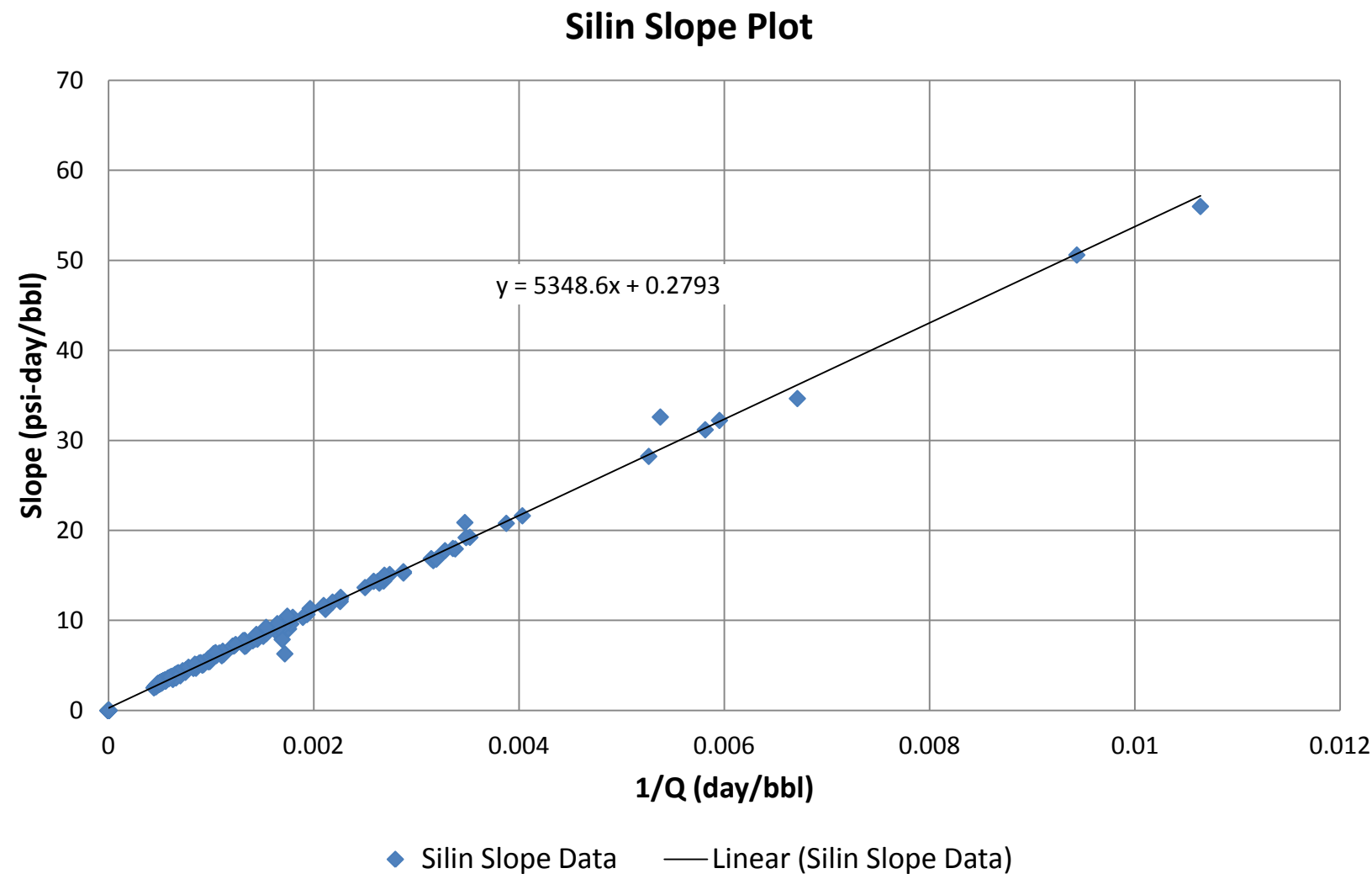


FIGURE G-11: NORTH STAR NO. 1 SWD TANDEM PLOT

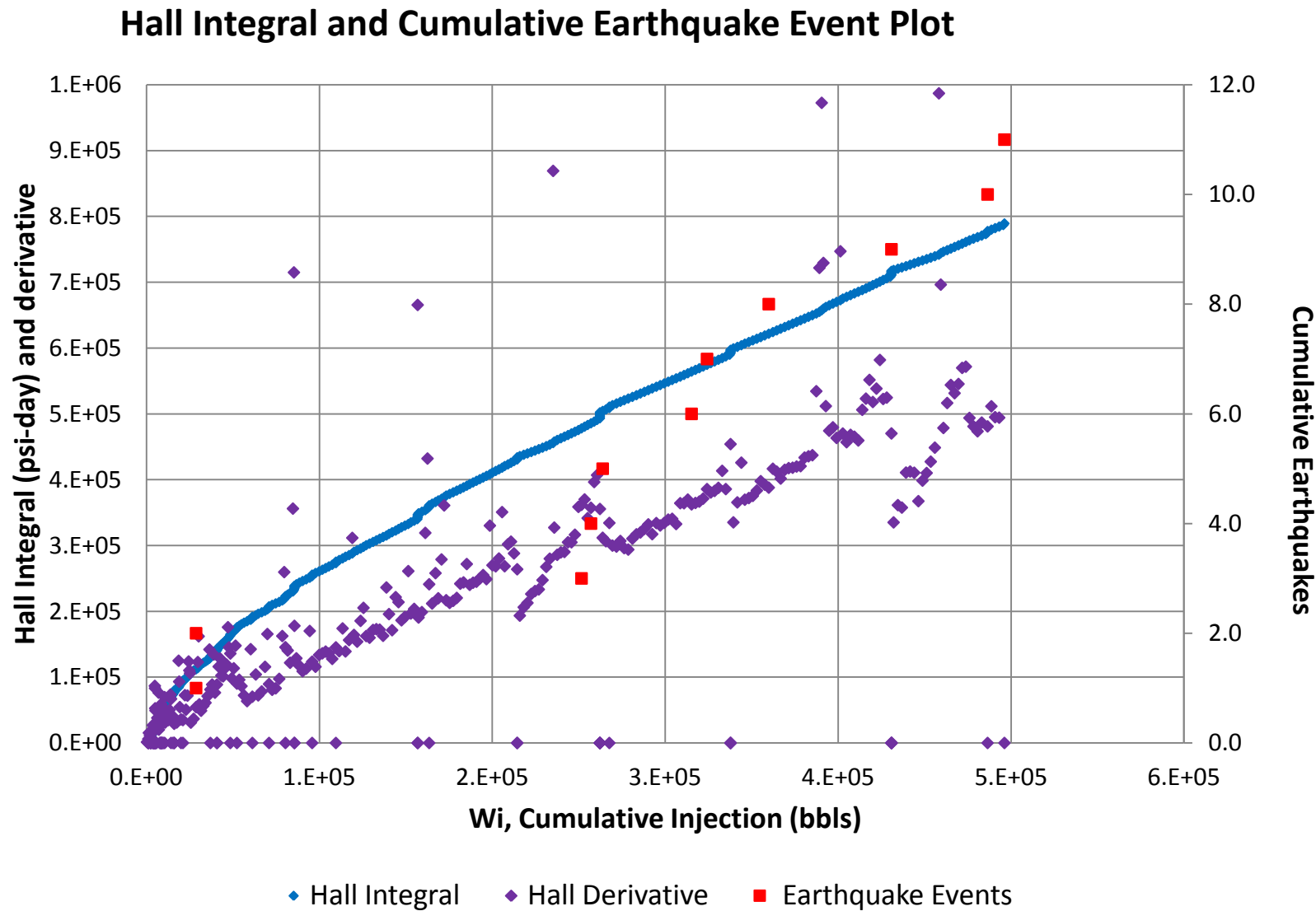
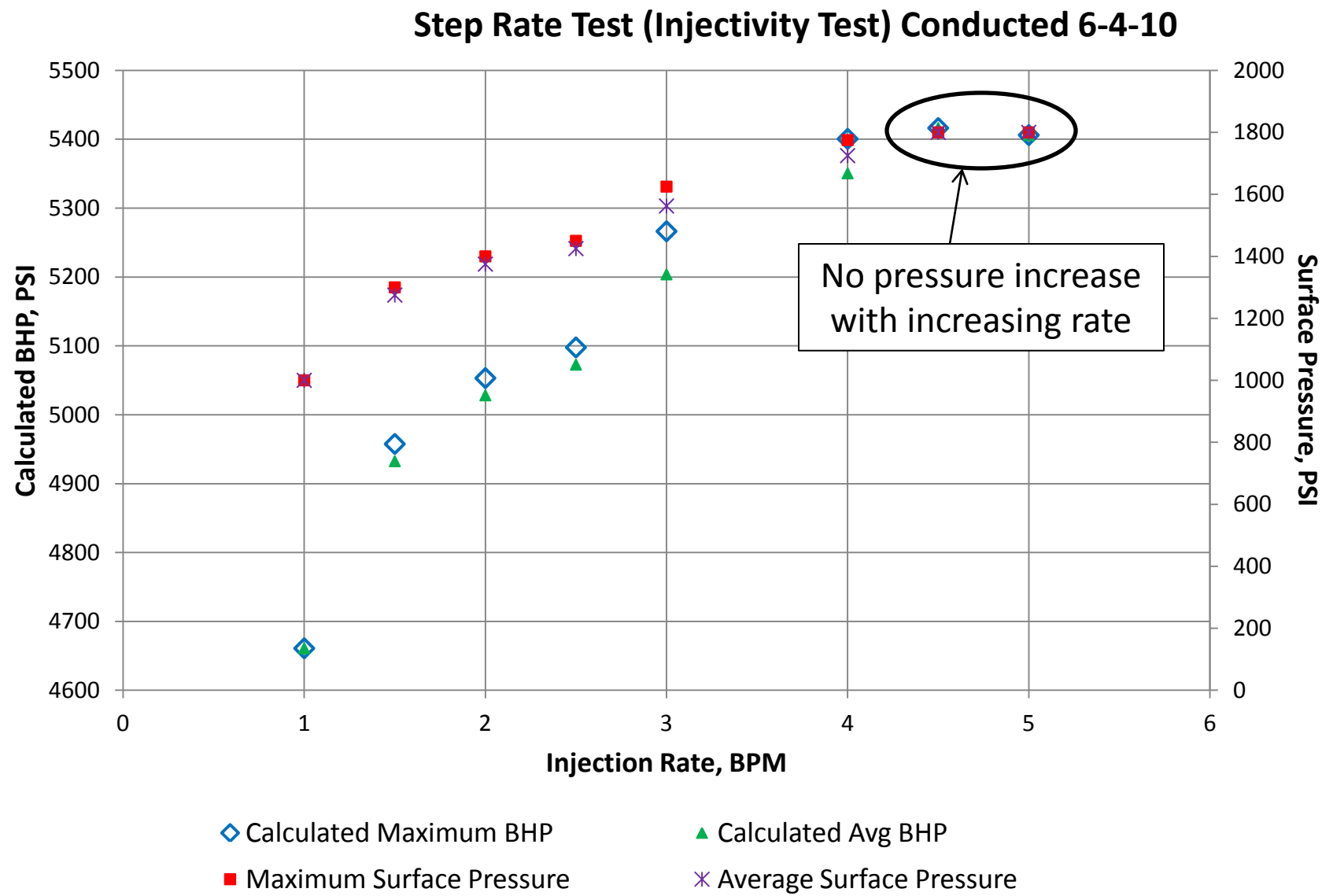


FIGURE G-12: NORTH STAR NO. 1 SWD JUNE 4, 2010 STEP RATE TEST



## APPENDIX H: NATIONAL ACADEMY OF SCIENCE PUBLICATIONS

Listing of included NAS publications:

- Block, L., 2011, Paradox Valley deep disposal well and induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, Bureau of Reclamation, US Department of the Interior.
- Dellinger, P., 2011, EPA actions on induced seismicity, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas, US Environmental Protection Agency.
- Eisner, L., 2011, Seismicity of DFW, Texas, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies, Dallas, Texas.
- Horton, S., and Ausbrooks, S., 2011, Earthquakes in central Arkansas triggered by fluid injection at Class 2 UIC wells, National Academy of Science Meeting of the Committee on Induced Seismicity Potential in Energy Technologies: Dallas, Texas.
- Johnson, D. O., 2011, Regulatory response to induced seismicity in Texas, Presented at National Academy of Sciences Meeting of the Committee on Induced Seismicity Potential in Energy Technologies, Dallas, Texas.

**Publications are not for review and have not been included during this prepublication review, but will be included in the final report.**

APPENDIX I: NON-SEISMIC RELATED EXAMPLE OF LARGE DISTANCE  
PRESSURE TRANSMISSION

## A Case History:

---

Non-seismic related example of large distance pressure transmission to orphan wells from the Wild Boar SWD No. 1 verified with falloff and interference testing

EPA Region 6 UIC Land Ban Staff

January 2012

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|--|-----|
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## *EXECUTIVE SUMMARY*

Two orphaned wells located in Caddo Parish, Louisiana, experienced an increase in surface pressure and were equipped with pressure gauges for monitoring in June 2004. Both orphan wells were completed in the Fredericksburg Formation. Additional investigation of other area Fredericksburg completed wells showed some wells with elevated fluid levels or positive surface pressure. A Fredericksburg gas well, the Rudd No. 4, located in Harrison County, Texas, reportedly watered out abruptly in December 2003.

A disposal well, the Wild Boar SWD No. 1, located in Harrison County, Texas, 150 feet inside the Texas - Louisiana border was completed in the Fredericksburg Formation and started injection in July 2003. This disposal well was identified as a potential source for the elevated reservoir pressure since it was the only area disposal well with an operating pressure exceeding the surface pressure measured at one of the orphaned wells.

In April 2004, EPA Region 6 staff developed an interference testing procedure to evaluate if the Wild Boar disposal well was hydraulically communicating with the Louisiana orphan wells and the watered out Texas gas well. The test also required monitoring fluid levels in wells located outside the suspected directional trend for a possible pressure response. EPA also coordinated monitoring and testing activities with the Texas and Louisiana regulatory agencies, the Railroad Commission of Texas (RRC) and Louisiana Department of Natural Resource (LDNR) Office of Conservation (OC), respectively. The operator of the watered out gas well, Wilcox Operating Company (Wilcox), and the operator of the Wild Boar SWD No. 1, Winchester Production

Company (Winchester) were also involved in the testing. EPA Region 6 staff reviewed and analyzed the resulting data.

Further discussion of the following conclusions along with testing activities and data analysis are provided within this case study. The primary conclusions were:

1. The Wild Boar SWD No. 1 was in direct hydraulic communication with some of the Louisiana orphaned wells located over a mile away.
2. There was a directional trend to the wells observing elevated pressure responses. The hydraulic communication response observed during the interference test confirmed the presence of a strong linear trend.
3. Analyses of the falloff test data indicated a linear flow trend representing non-homogeneous reservoir behavior at the Wild Boar SWD No. 1.
4. Elevated pressures from the disposal well exceeded the  $\frac{1}{4}$  mile area of review (AOR) allowed for Class II underground injection control (UIC) permits.
5. The geologic characteristics of the Fredericksburg Formation surrounding the Wild Boar SWD No. 1 were poorly understood. The reservoir's linear flow behavior or "fluid conduit" could not be explained based on review of available geologic and reservoir information. Uncertainty in geological characterization of injection intervals should be considered in future permitting activities.
6. Pressure transient testing at the injection well provided a successful methodology for identifying non-homogeneous, non-radial flow disposal reservoir behavior.

## **BACKGROUND**

The case study area was located along the border of Harrison County, TX and Caddo Parish, LA, near the Texas town of Waskom and just west of Shreveport, LA (Attachment 1). In February 2004, Louisiana's LDNR OC identified elevated surface pressure in two orphaned wells located approximately one mile east of the Texas border (Attachment 2). Pressure gauges were installed on these two orphaned wells, Anisman No. 17 and Abney No. 17 to monitor the pressure.

Well records indicated both orphan wells were completed in the Fredericksburg Formation. In Louisiana, most of the wells illustrated on Attachment 2 were drilled in the late 1950s and early 1960s. A second wave of drilling occurred in the early 1980s with few wells drilled in between. The search for additional wells and a potential pressure source identified the Anisman No. 4, another shut-in Fredericksburg well with positive surface pressure.

On the Texas side an updip Fredericksburg gas well, the Rudd No. 4 operated by Wilcox watered out in December 2003. The gas well operator noted the produced water from his other Fredericksburg gas well had a chloride concentration of 25,000 mg/l, however the sample from Rudd No. 4 had a chloride concentration of 69,000 mg/l making him suspicious of where the



water was coming from. The operator tested his gas well and found no casing leak. Most of the Rudd gas wells were drilled since 2000 with the Rudd No. 4 being drilled and completed in May 2002.

The only recent disposal well authorized into the Fredericksburg Formation was Winchester's Wild Boar SWD No. 1 shown in Attachment 3. The Wild Boar SWD No. 1 is located just southeast of the town of Waskom, TX.

EPA Region 6 staff visited the area of the purging wells and met with representatives of Wilcox, the operator of the watered out gas well, and Winchester, the operator of the Wild Boar SWD No. 1.

### *GEOLOGY*

A cross-section location map of the impacted wells shown in Attachment 4 suggested a linear trend. The Anisman No. 7 also located along the trend line did not experience any pressure at the surface. A cross-section of the wells along the trend line shows the top of the Fredericksburg is around 2300' KB (Attachment 5). The completed intervals for individual wells varied in depth. No direct geologic evidence of fractures was identified, however the stratigraphic chart showed the Fredericksburg underlying an unconformity (Attachment 6). The study area is located on the northern crest of the Sabine Uplift (Attachment 7). A surface lineament map indicated features with similar SW-NE orientation (Attachment 8).

The type of production from the Fredericksburg Formation is dependent on a well's structural location and date drilled. The Fredericksburg Formation is structurally higher on the Texas side of the border. The Rudd Lease wells are gas wells, with seven of the eight wells drilled since 2000. In Louisiana, the Fredericksburg wells had been oil productive.

### *TEST DESIGN*

EPA Region 6 management agreed to help facilitate an interference test between the Wild Boar SWD No. 1 and the orphan wells in Louisiana. An interference test procedure was prepared by EPA Region 6 to determine if the Wild Boar SWD No. 1 impacted the offset Fredericksburg wells in Texas and Louisiana. Given the SWD was located in Texas and orphaned wells were in Louisiana, the test took a cooperative effort between LDNR OC and RRC.

The primary goal of the test was to identify if communication existed between wells and establish repeatability of pressure responses if communication was present. Surface pressure transducers were installed on the Abney No. 17, Anisman No. 17, Anisman No. 4, Wild Boar SWD No. 1, and the Rudd No. 4 to monitor pressures during the test. Additional wells, shown as blue dots in Attachment 9 represented wells selected for fluid level monitoring. The

monitoring wells selected were located at various angles from the SWD to check for other directional trends. Wells located inside the dashed line in Attachment 9 were classified “near observer” wells for fluid level monitoring, while the wells outside the dashed ring were noted as “far observer” wells for fluid level monitoring. The frequency of fluid level readings were designed to provide more data immediately following a rate change at the disposal well and then less frequent monitoring later during that event sequence. Acquiring more early data is critical when the data is plotted on a log scale.

Personnel from LDNR’s Shreveport office used echometers to measure all the fluid levels and also downloaded the electronic data from the pressure transducers from all the offset wells. The operator of the Wild Boar agreed to have their data downloaded weekly and then submitted the data to EPA and corresponding state agencies.

A timeline of the interference test is included in Attachment 10. The interference test consisted of a background period, stabilization period, injection period, falloff period, and post-test period.

#### BACKGROUND PERIOD

During the background period, surface readout pressure gauges were installed on the three Louisiana wells that exhibited surface pressure. The operator of the Wild Boar agreed to install an electronic pressure gauge and inline flow meter on the disposal well, and the gas well operator also opted to install a pressure transducer on the Rudd No. 4 (Attachment 11). In addition to surface pressure readings, fluid levels were taken at the remaining monitoring locations.

#### STABILIZATION PERIOD

During the one week stabilization period, the Wild Boar SWD No. 1 was shut-in. Monitoring continued as designed at the monitoring well locations. During this time, lightning hit the Wild Boar SWD injection facility, damaging the tanks, injection pump and transformers. (Attachment 12). No critical pressure data was lost. The operator brought in frac tanks, got the injection pump rebuilt, and transformers reset. This only prolonged the stabilization period of the test for a couple of additional days, so the timeline was revised and the injection and falloff periods were shifted accordingly.

#### INJECTION PERIOD

During the injection period, constant injection was initiated in the Wild Boar SWD No. 1. Although the Wild Boar SWD No. 1 did not typically run 24 hours a day, seven days a week, the

operator agreed to operate the well continuously at as constant a rate as possible during the injection period. Monitoring of the offset wells continued as scheduled.

#### **FALLOFF PERIOD**

During the falloff period, injection into the Wild Boar SWD No. 1 ceased and the pressure falloff recorded at the disposal well. Monitoring of the offset wells continued as scheduled.

#### ***PRESSURE RESPONSES***

The pressure response between the Wild Boar SWD No. 1 and the Anisman No. 17, Abney No. 17, and Anisman No. 4 indicated communication (Attachment 13). The repeatability of the results was observed in all three Louisiana wells with surface pressure. The wellbore configuration of the Rudd No. 4 impacted acquisition of the pressure data so it was excluded. The lag time for the pressure response was much faster than anticipated and definitely not typical of a radially homogeneous reservoir (Attachment 14). The Anisman No. 4 is located approximately a quarter mile from the Wild Boar SWD No. 1 whereas the Anisman No. 17 and Abney No. 17 are located about a mile away from the SWD; however, the response times were not significantly different. The magnitude of the pressure response varied, but a significant pressure response was still observed.

The fluid levels monitored during the test did not suggest any communication with the Wild Boar SWD No. 1 (Attachment 15). Other than the Anisman No. 4, the other three wells located closest to the SWD are shown in Attachment 16 and had no pressure response corresponding to the rate changes at the source well. There appeared to be no additional directional pressure trends observed in the data.

#### ***ANALYSIS***

##### **WILD BOAR SWD No. 1 FALLOFF TESTS**

An overview plot of the injection rates and pressure measured at the Wild Boar SWD No. 1 are included in Attachment 17. Following injection of 1728 bpd, the pressure declined from about 860 psi to 430 psi during the initial stabilization period. Pressure at the end of the stabilization period was declining a little more than 0.5 psi/hr. There were a few rate fluctuations during the injection period resulting in noisy data which is often the case with injectivity tests. The quieter falloff period in an injection well or buildup period in a production well typically provides better quality data which was the case with this test. EPA Region 6 staff analyzed both periods of pressure decline from the stabilization and falloff periods.

Attachment 18 illustrates the typical log-log plot for a radially homogenous infinite acting reservoir. The log-log plots for the Wild Boar SWD No. 1 during the stabilization and falloff periods were not similar to these characteristics (Attachment 19). A quarter slope trend was observed for the entire test period during the stabilization period and for a portion of the falloff test. Quarter slope trends are typically seen during the early stages of tests conducted in hydraulically fractured wells. The falloff period also had a half slope following the quarter slope usually associated with a highly conductive fracture.

An attempt was also made to simulate the results using PanSystem<sup>®</sup> pressure transient software. The simulated results resulted in a very low permeability and unrealistically long fracture half length nearing a mile in length (Attachment 20). This fracture half length is unrealistic, but suggests the well was in communication with some type of linear fracture or fault system.

#### MONITORING WELL INTERFERENCE TESTS

Efforts were made to analyze the pressure responses recorded at the three Louisiana wells. The Anisman No. 17 was located 4971' from the source disposal well, the Abney No. 17 was 5826' from the source well and the Anisman No. 4 was located only 1231' from the source well. Prior to starting the test design, a response was simulated for the wells using the reservoir parameters listed in the permit. The simulations indicated it should take weeks before any pressure response was observed in the two distant wells and the pressure response was so small it would likely not be measurable. However, the measured responses at all three wells was an easily measurable level which occurred soon after a rate change at the Wild Boar SWD No. 1 (Attachment 14). Quantitatively, the pressure responses indicated a very high transmissibility connection to the source disposal well as well as a nonhomogeneous behavior. This characteristic was obvious from the immediate pressure response observed at the wells following a rate change at the Wild Board SWD No. 1. A pressure transient analysis of the pulse test yielded marginal results due to the short lag times and magnitude of the pressure changes relative to the entire pulse cycle. All the measured results pointed out the uncharacteristic nature of the Fredericksburg Formation.

A typical response seen in an observation well during an interference test can usually be plotted on a log-log plot and evaluated by type curve matching the results using the Ei type curve shown on Attachment 21. The responses measured at the three wells with surface pressure all happened outside the range of the Ei type curve. The log-log plot of the Anisman No. 4 measured data shown in Attachment 22 exhibited a naturally fractured reservoir characteristic or indication of directional permeability in the early time curvature response veering off the Ei type curve. The type curve match of the middle time data gave an unrealistically high permeability. The late time data had little to no curvature.

As illustrated in Attachment 23, an early time match of the Anisman No. 17 measured data gave even a more unrealistically high permeability, whereas a much lower effective permeability resulted from the match of the late time data. The log-log plot of measured data from the Abney No. 17 also could not be matched to the Ei type curve as shown in Attachment 24.

## *CONCLUSIONS*

1. The log-log plots of the Wild Boar SWD No. 1 falloff periods both indicated the well was connected to some type of fracture or fault system even though this type of geologic environment was not evident from available geologic data.
2. Pressure transient test analyses of the pulse and interference test data were marginal at best. The naturally fractured signature observed in the early time data on several of the log-log plots suggested a non-homogeneous reservoir behavior.
3. Though typical interference analysis could not be performed on the pressure responses, the repeatability of the pressure responses showed the Wild Boar SWD No. 1 was in direct communication with some of the Louisiana wells located along the SW-NE trend line.
4. Increase in water production and higher chloride measurements in the Rudd No. 4 suggested potential communication with the Wild Boar SWD No. 1.
5. Given that Texas had permitting authority over the disposal well in question and the orphan wells were located in Louisiana, the partnership between the state regulatory agencies was essential during both the planning and execution of the test.
6. Regulators may consider conducting a pressure transient test in a disposal well to better characterize the reservoir in new disposal zones.
7. If appropriate, the AOR for wells in non-homogeneous reservoirs may need to be expanded.
8. Some of the pressure and fluid level variations and the lack of response observed in the Louisiana orphaned wells tested may represent issues related to the well's configuration, completion into a different formation, or lack of mechanical integrity. Therefore, the lack of response during the interference test was not entirely conclusive.
9. Pressure transient testing of the disposal well provided a successful method for identifying non-homogeneous, non-radial flow disposal reservoir behavior.

## *RESULTS*

In July 2004, the RRC requested Winchester immediately cease injection into the Wild Boar SWD No. 1. The well was later plugged and abandoned. Elevated pressures observed in the Louisiana wells dissipated. The LDNR OC initiated the plugging of several Caddo Parish orphaned wells.

In October 2004, LDNR OC and RRC entered into a memorandum of understanding to provide each other 15 day written notice prior to any proposed approval of injection activity within one mile of the border.

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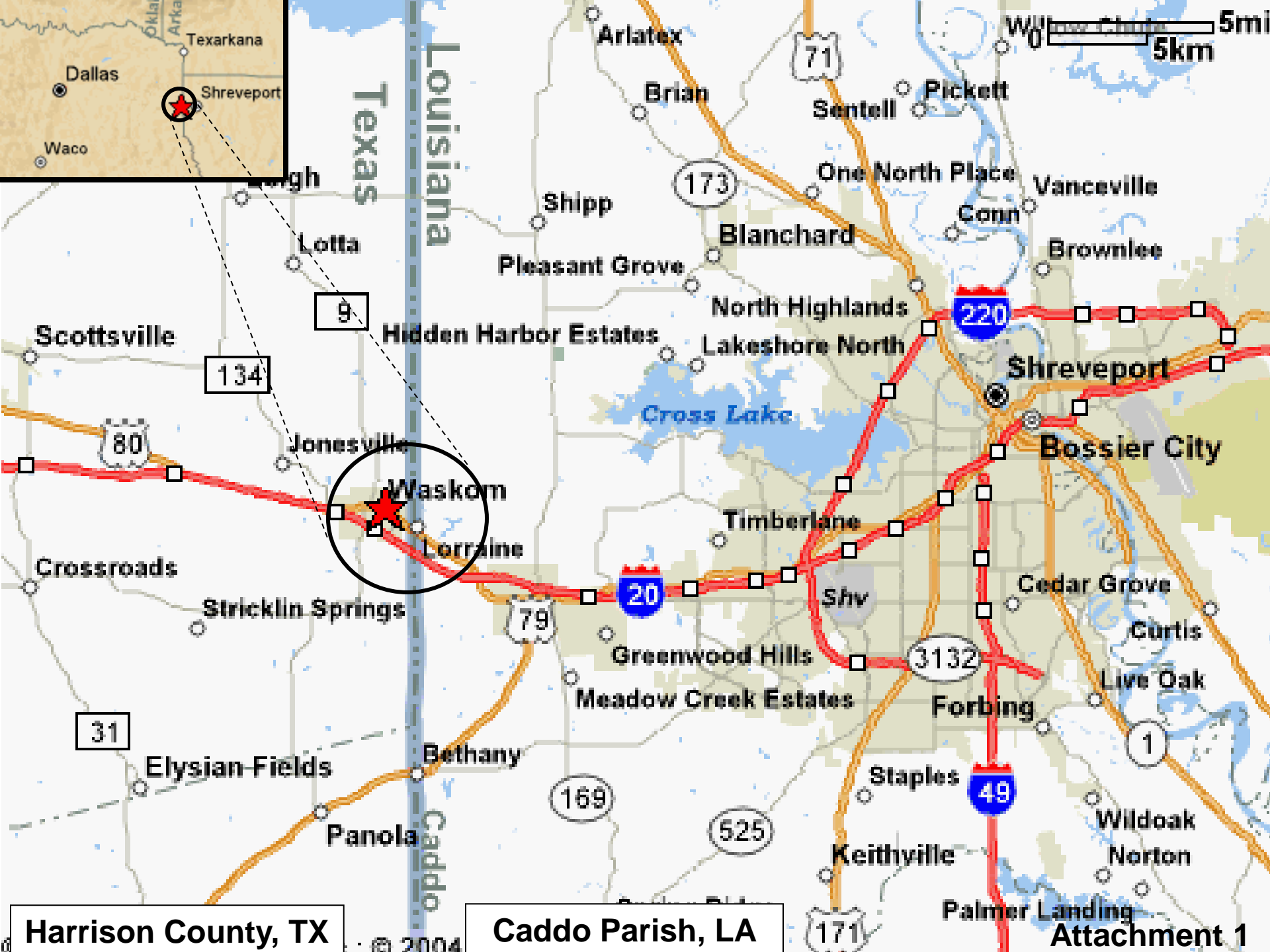
## *ACKNOWLEDGMENTS*

EPA Region 6 thanks Robert Gray, Randy McLaughlin, Pete Bradford, and Rex Darden with Louisiana Department of Natural Resource Office of Conservation for their time and tremendous effort obtaining the information used in this case study.

## *LIST OF ATTACHMENTS*

| <u>Number</u> | <u>Content</u>   |
|---------------|--|
| 1             | Map identifying case study area  |
| 2             | Location of LA orphan wells from Wild Boar SWD   |
| 3             | Pictures of Wild Boar SWD No. 1 and injection facility   |
| 4             | Cross-section Location Map   |
| 5             | Stratigraphic cross-section A-A'   |
| 6             | Stratigraphic chart  |
| 7             | Sabine Uplift; USGS; 1974  |
| 8             | Lineament Surface Density Map; Baumgardner; 1987   |
| 9             | Location of near and far wells for fluid level monitoring  |
| 10            | Wild Boar SWD No. 1 interference and falloff testing timeline  |
| 11            | Measurement devices at the Wild Boar SWD No. 1 and Rudd No. 4  |
| 12            | Wild Boar SWD No. 1 injection facility before and after lightning strike                               |
| 13            | Wild Boar SWD No. 1 injection rate and three LA well pressure responses                                |
| 14            | Time lag between surface pressure response at LA well locations and rate change at Wild Boar SWD No. 1 |

|    |  |
|----|--|
| 15 | Fluid level responses at wells with no surface pressure recorder               |
| 16 | Fluid level responses at Anisman No. 7, Anisman No. 10, and Anisman No. 12     |
| 17 | Wild Boar SWD No. 1 measured pressure and injection rates                      |
| 18 | Typical log-log plot responses for a homogeneous infinite acting reservoir     |
| 19 | Wild Boar SWD No. 1 log-log plots during the stabilization and falloff periods |
| 20 | Simulated response during the stabilization and falloff periods                |
| 21 | Typical interference test responses - Ei type curve                            |
| 22 | Anisman No. 4 log-log plot of the falloff period                               |
| 23 | Anisman No. 17 log-log plot of the injection period                            |
| 24 | Abney No. 17 log-log plot of the stabilization period                          |



Harrison County, TX

Caddo Parish, LA

Attachment 1



Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

Wild Boar SWD

Lorraine

Spillway

Elevation 228

Pipeline

Slate Line Lake

240

250

233

229

218

217

216

215

214

213

212

211

210

209

208

207

206

205

204

203

202

201

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17

16

15

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4

3

2

1

0

Attachment 2

Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

SPILLWAY ELEVATION 228

Lorraine

Wild Boar SWD

Slack Line Lake

Attachment 2

Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

Wild Boar SWD

Attachment 2

Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

Spillway Elevation 228

Lorraine

Wild Boar SWD

Attachment 2

Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

Spillway Elevation 228

Lorraine

Wild Boar SWD

Attachment 2

Approximately 1 mile from TX-LA border

TX LA

Anisman #17

Abney #17

Spillway Elevation 228

Lorraine

Wild Boar SWD

Attachment 2

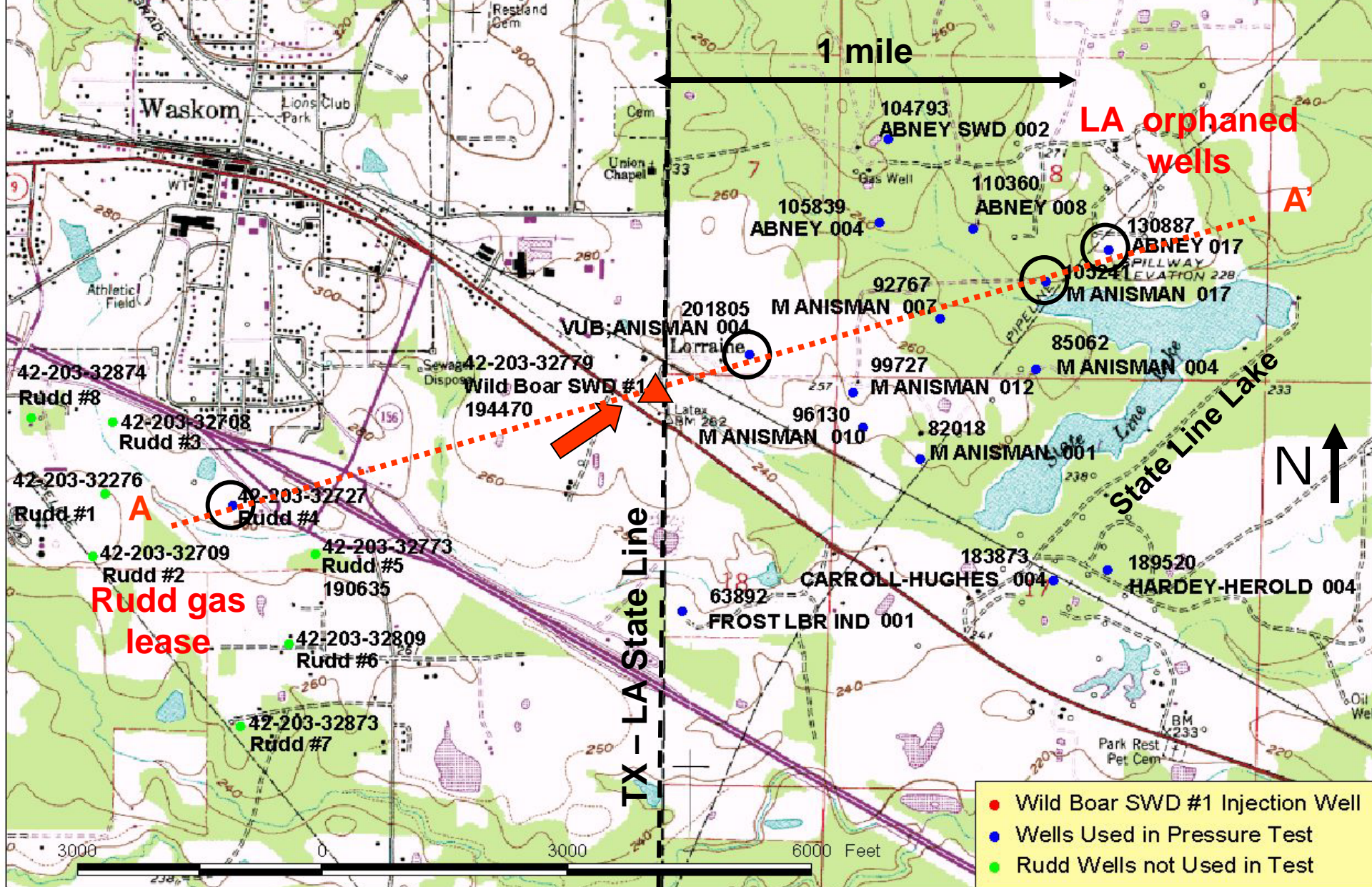




# Wild Boar SWD #1







**Harrison County, TX**

**Caddo Parish, LA**

**Attachment 4**



# Stratigraphic Cross-section A-A'

**TX #190635**  
**Rudd #4**  
**Lipscomb Survey**  
**A-404**

**TX RRC # 194470**  
**Wild Boar SWD #1**  
**E. Pollock Survey A-566**

**LA SN: 201805**  
**Anisman #4**  
**Sec 7-17N-16W**

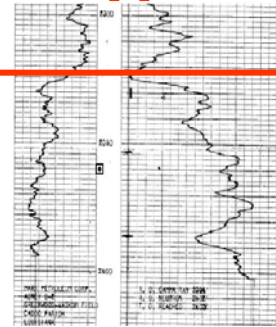
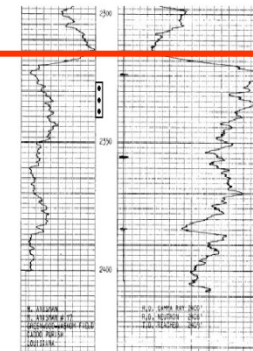
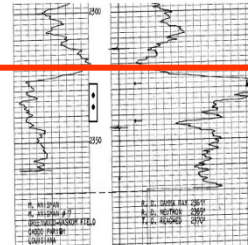
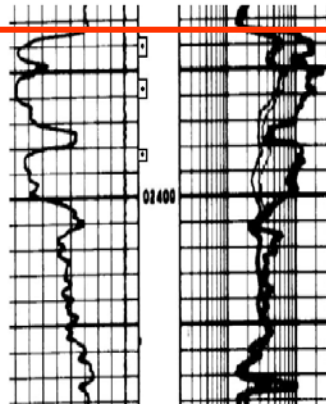
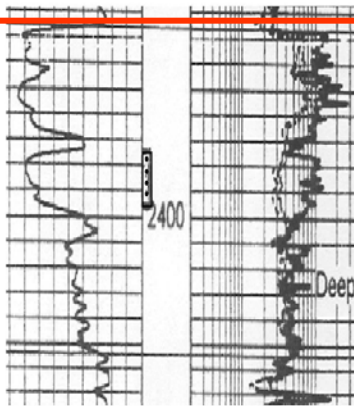
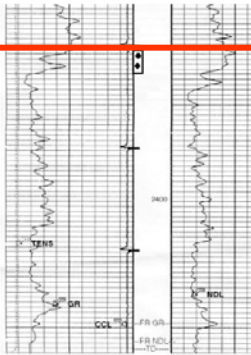
**LA SN: 92767**  
**Anisman #7**  
**Sec 8-17N-16W**

**LA SN: 105241**  
**Anisman #17**  
**Sec 8-17N-16W**

**LA SN: 130887**  
**Abney #17**  
**Sec 8-17N-16W**

**A** **Top of Fredericksburg Formation**

**A'**



**Fredericksburg**  
**Perfs:**  
2340'-2350'  
PBTD: 2447'  
TD: 2450'

GL: 258'  
D&C: 5/02  
IP: 16 BO/0 MCF  
? BW per day  
Acidz: 10000 gal  
15% Hydrochloric  
H15

**Fredericksburg Perfs:**  
2376'-96'  
PBTD: 2957'  
Log TD: 3015'  
TD: 3000'

GL: 259  
Spud: 3/03  
First Injection: 7/03

**Fredericksburg Perfs:**  
2338'-44',  
2354'-60',  
2380'-85'  
PBTD: 2463'  
w/ CIBP  
Log TD: 3887'  
TD: 3890'

GL: 266  
D&C: 1/86 Glen Rose  
Recomplete:  
6/95 Paluxy  
Recomplete:  
3/96 Fredericksburg  
IP: 2 BO/6 MCF  
4 BW per day

**Fredericksburg Perfs:**  
2328'-2342'  
Log TD: 2370'  
TD: 2417'

GL: 246  
D&C: 12/62  
IP: 5 BO/? MCF  
?BW per day  
Acidz: 2000 gal 15%  
Frac'd w/ 1800 BW  
70000# sd

**Fredericksburg Perfs:**  
2326'-2340'  
TD: 2424'  
PBTD: 2409'

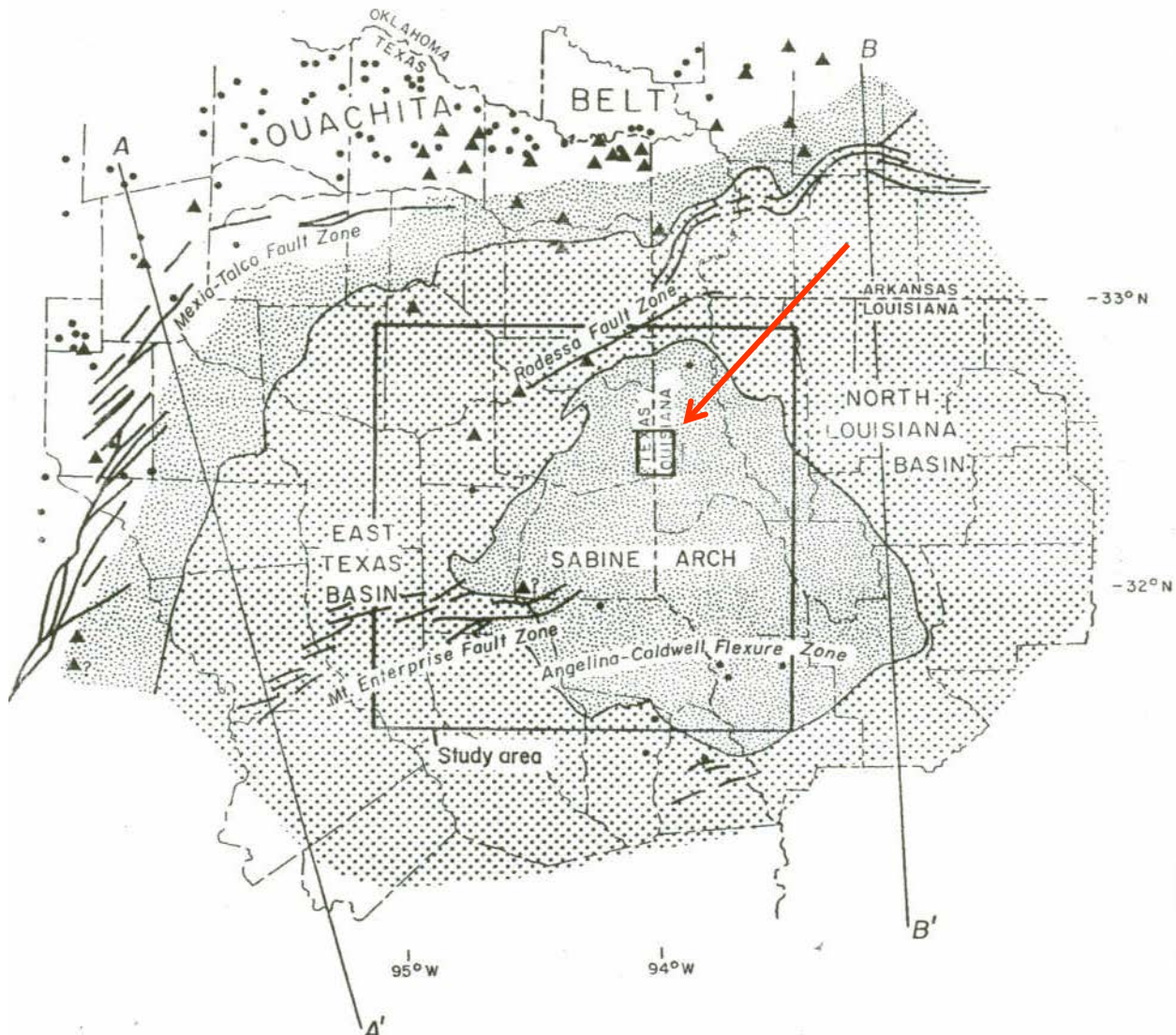
GL: 232'  
D&C: 11/64  
IP: 14 BO/0 MCF  
? BW per day  
Frac'd w/ 2100 BW  
50000# sd

**Fredericksburg Perfs:**  
2358'-2362'  
Log TD: 2403'  
TD: 2416'

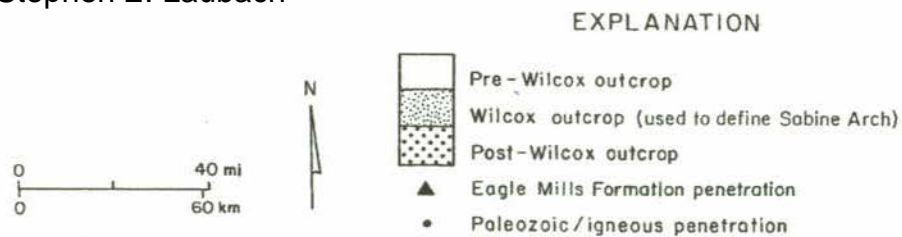
GL: ?'  
D&C: 12/70  
IP: 16 BO/0 MCF  
?BW per day  
Acidz: 4000 gal

# Stratigraphic Chart

| ERA      | SYSTEM      | SERIES                      | GROUP                 | FORMATION          |                                   | Thickness<br>In Feet |                                      |             |           |  |           |
|----------|-------------|-----------------------------|-----------------------|--------------------|-----------------------------------|----------------------|--------------------------------------|-------------|-----------|--|-----------|
| CENOZOIC | QUATERNARY  | RECENT                      |                       | Recent Alluvium    | SURFACE                           | Undiff.              |                                      |             |           |  |           |
|          |             |                             |                       | Deweyville         |                                   |                      |                                      |             |           |  |           |
|          |             | PLEISTOCENE                 | TERRACE<br>DEPOSITS   | Frannie            |                                   | Undiff.              |                                      |             |           |  |           |
|          |             |                             |                       | Montgomery         |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | Bentley            |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | Williana           |                                   |                      |                                      |             |           |  |           |
|          |             | PLIO-<br>PLEISTOCENE        | Unconformity          |                    |                                   |                      |                                      |             |           |  |           |
|          |             | MIOCENE                     | Unconformity          | (Undifferentiated) |                                   |                      |                                      | ?           |           |  |           |
|          |             | OLIGOCENE                   | (Undifferentiated)    | 55 + - ?           |                                   |                      |                                      |             |           |  |           |
|          |             | TERTIARY                    | JACKSON               | (Undifferentiated) |                                   |                      |                                      | 600 ± - 753 |           |  |           |
|          |             |                             |                       | CLAIBORNE          |                                   | Cockfield            | ? - 912                              |             |           |  |           |
|          |             |                             | Cook Mountain         |                    |                                   | 120 ± - 328          |                                      |             |           |  |           |
|          |             |                             | Sparta                |                    |                                   | 180 ± - 446          |                                      |             |           |  |           |
|          |             |                             | Cane River            |                    |                                   | 80 ± - 252           |                                      |             |           |  |           |
|          |             |                             | EOCENE                | WILCOX             |                                   | Carrizo              | Undifferentiated<br>In Subsurface    | 512 - 3,637 |           |  |           |
|          |             |                             |                       |                    |                                   | Sabinetown           |                                      |             |           |  |           |
|          |             |                             |                       |                    |                                   | Pendleton            |                                      |             |           |  |           |
|          |             |                             |                       |                    |                                   | Marthaville          |                                      |             |           |  |           |
|          |             |                             |                       |                    |                                   | "Hall Summit"        |                                      |             |           |  |           |
|          |             |                             |                       |                    |                                   | Lime Hill            |                                      |             |           |  |           |
|          | Converse    |                             |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | Cow Bayou   |                             |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | Dolet Hills |                             |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | Noborton    |                             |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | MIDWAY      | Porters Creek               | 750 - 1,097           |                    |                                   |                      |                                      |             |           |  |           |
|          |             | Kincaid                     | SUBSURFACE            |                    |                                   |                      |                                      |             |           |  |           |
|          | NAVARRO     | Arkadelphia                 |                       |                    | Undifferentiated<br>In Subsurface | 191 - 373            |                                      |             |           |  |           |
|          |             | Nacatoch                    |                       |                    |                                   |                      |                                      |             |           |  |           |
|          |             | Saratoga                    |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | TAYLOR      | Marlbrook                   |                       |                    | Undiff.<br>In Subsur.             | 61 - 133             |                                      |             |           |  |           |
|          |             | Annona                      |                       |                    |                                   |                      | 93 - 215                             |             |           |  |           |
|          |             | Ozan                        |                       |                    |                                   |                      |                                      |             |           |  |           |
|          | AUSTIN      | Brownstown                  |                       |                    | Undiff.<br>In Subsur.             | 665 - 980            |                                      |             |           |  |           |
|          |             | Tokio                       |                       |                    |                                   |                      |                                      |             |           |  |           |
|          |             | Ector Chalk                 |                       |                    |                                   |                      | 75 - 195                             |             |           |  |           |
|          |             | (Undifferentiated)          | 60 - 242              |                    |                                   |                      |                                      |             |           |  |           |
|          | EAGLE FORD  | (Undifferentiated)          | Undiff.<br>In Subsur. | 65 - 385           |                                   |                      |                                      |             |           |  |           |
|          |             | WASHITA -<br>FREDERICKSBURG |                       |                    | 973 - 1,217                       |                      |                                      |             |           |  |           |
|          | CRETACEOUS  | COMANCHE                    | TRINITY               | Paluxy             | Undiff.<br>In Subsur.             | 1,515 - 1,740        |                                      |             |           |  |           |
|          |             |                             |                       | Mooringsport       |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | Ferry Lake         |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | Rodessa            |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | James              |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | Pine Island        |                                   |                      |                                      |             |           |  |           |
|          |             |                             |                       | COAHUILA           |                                   |                      | NUEVO LEON &<br>DURANGO<br>OF MEXICO | Sligo       | 250 - 350 |  |           |
|          |             |                             |                       |                    |                                   |                      |                                      | Hosston     | 91 - 122  |  |           |
|          |             |                             |                       |                    |                                   |                      |                                      |             |           |  | 663 - 725 |
|          |             |                             |                       |                    |                                   |                      |                                      |             |           |  | ? - 3,062 |



Taken from Geologic Circular 91-3, Structural History and Origin of the Sabine Arch, East Texas and NW Louisiana by Mary L.W. Jackson and Stephen E. Laubach



QA 7037



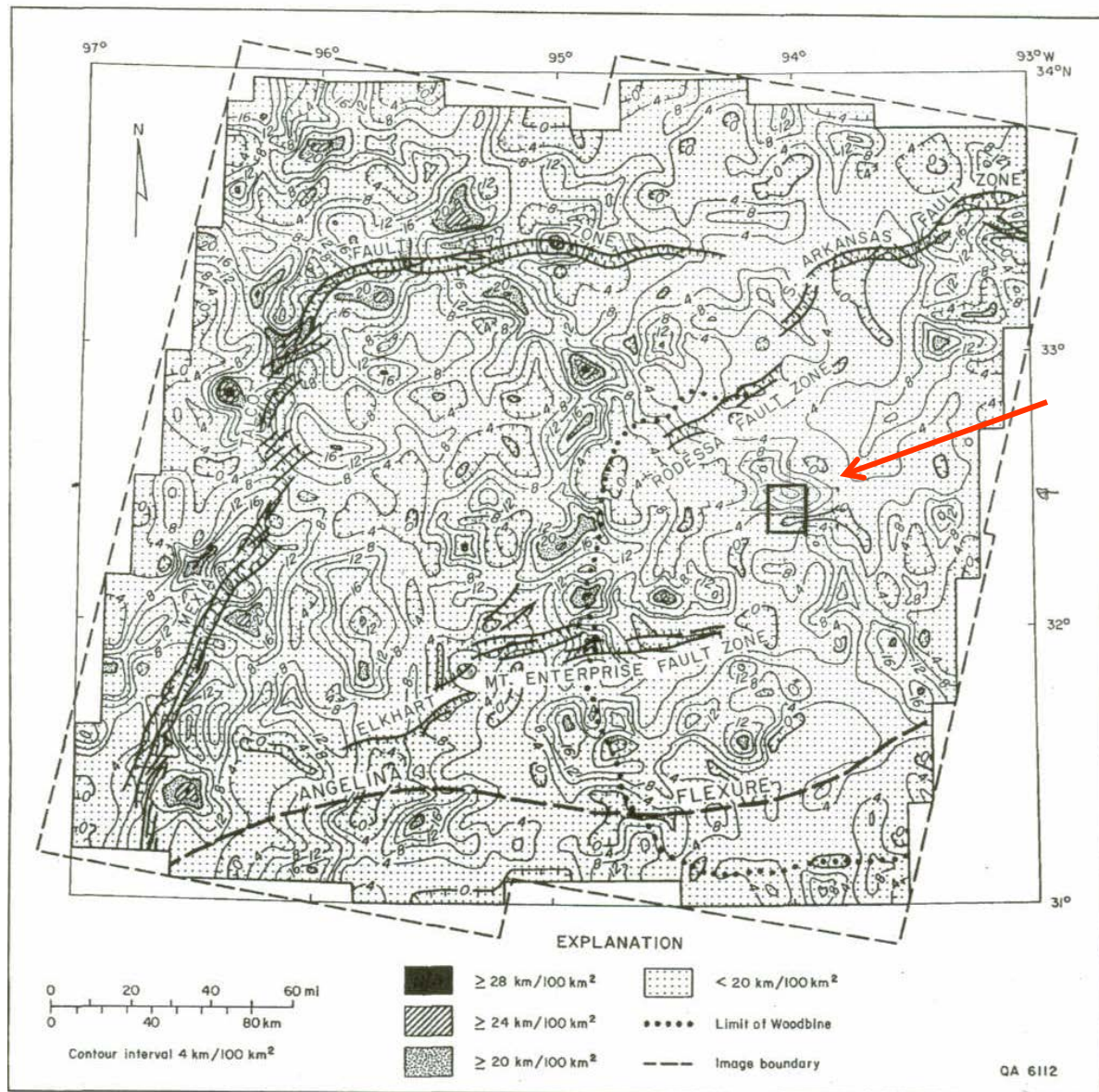
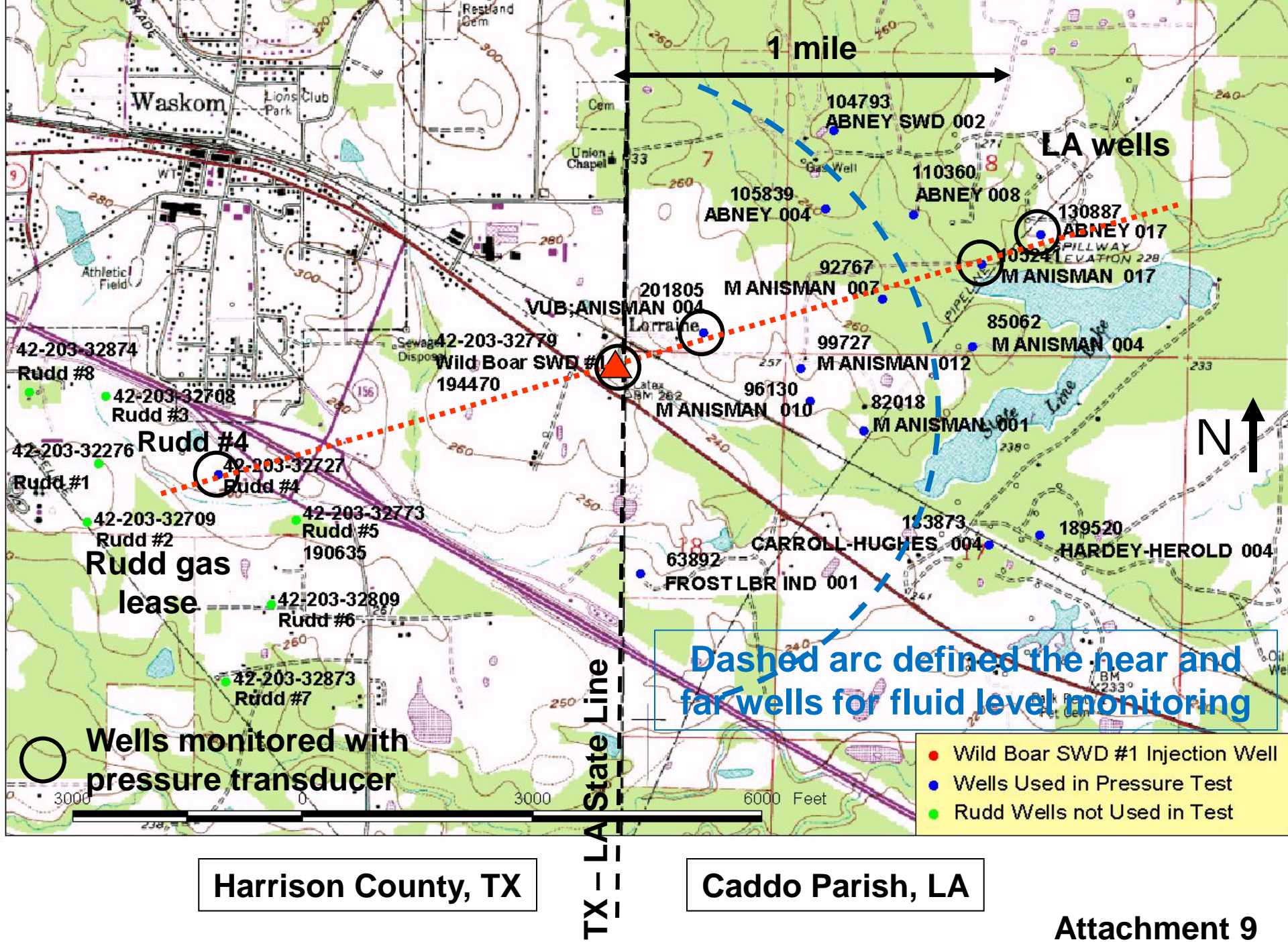


FIGURE 12. Map of lineament density ( $\text{km}/100 \text{ km}^2$ ) and major structural features. High values demarcate the Mexia-Talco Fault Zone and other structural features. See figure 1 for location of study area.

Taken from Landsat-Based Lineament Analysis, Sabine Uplift Area; Report of Investigations No. 167, Bureau of Economic Geology; 1987 by R.W. Baumgardner, Jr.







## Wild Boar Testing Timeline – Revised 6-22-04

|  | Period<br>June 15  | Period<br>June 24   | Period<br>July 1   | Period<br>July 8   | Period   |
|--|--|---|--|--|--|
| Wild Boar SWD # 1  | Normal Operations<br>Get <b>daily</b> rates and pressures - Install pressure transducer and rate meter | Shut-in for at least 7 days - Take surface pressure readings <b>twice daily</b> in addition to pressure transducer  | Constant rate inject for 7 days – Take rate and surface pressure readings <b>twice daily</b> in addition to pressure transducer  | Shut-in for 7 days – Take surface pressure readings <b>twice daily</b> in addition to pressure transducer  | Normal Operations<br>Get <b>daily</b> rates and pressures  |
| Near Monitor Wells<br>SN 63892<br>SN 82018<br>SN 92767<br>SN 96130<br>SN 99727<br>SN 105839<br>SN 201805 *                 | Take a minimum of <b>3</b> fluid levels or pressure readings per well <b>during this period</b>        | <b>June 15-20:</b> Take a minimum of <b>1</b> fluid level or surface pressure reading <b>daily for each well</b><br><br><b>June 23:</b> Take a minimum of <b>1</b> fluid level or surface pressure reading at each monitoring well. | <b>June 24 –30</b> (1 week): Near and far monitoring wells: Take <b>1 daily</b> fluid level or surface pressure reading. Measurement frequency may be increased for a well depending on response observed. | <b>July 1–July 7</b> (1 week): Near and far monitoring wells: Take <b>1 daily</b> fluid level or surface pressure reading. Measurement frequency may be increased for a well depending on response observed. | <b>July 8-22</b> (2 wks)<br>Take a minimum of <b>1</b> fluid level <b>3 times per week</b> for each monitoring well. (Suggest M-W-F) |
| Far Monitor Wells<br>Rudd #4 *<br>SN 85062<br>SN 104793<br>SN 105241 *<br>SN 110360<br>SN 130887<br>SN 183873<br>SN 189520 |  | At least 12 hrs prior to June 22, install pressure transducers on select monitoring wells *   |  |  |  |
|  |  | Stabilization start time: <u>9:52 am</u> June 15, 2004  | Injection period start time: <u>8:19 am</u> June 24, 2004  | Falloff period start time: <u>8:19 am</u> July 1, 2004   |  |

## Attachment 10

# Attachment 10

**Note date and time of every fluid level or pressure reading throughout all testing periods**

**Wild Boar SWD No. 1  
Inline flow meter and  
surface pressure  
transducer installed**



**Surface pressure  
transducer used on  
LA wells and TX gas  
well**

**Attachment 11**





One fiberglass  
storage tank



After

Temporary storage tank arrangement after  
lightning strike



Before



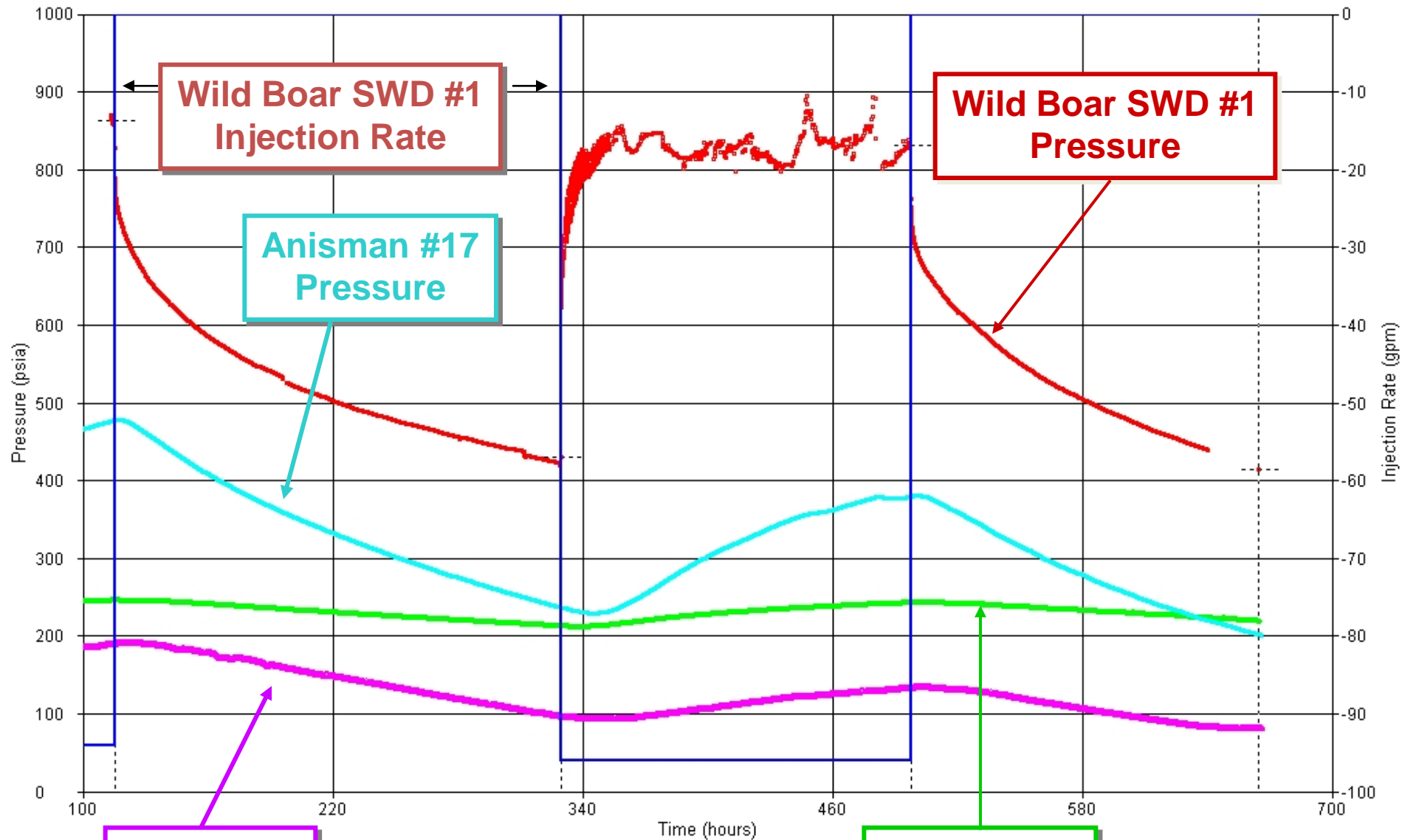
After

Attachment 12

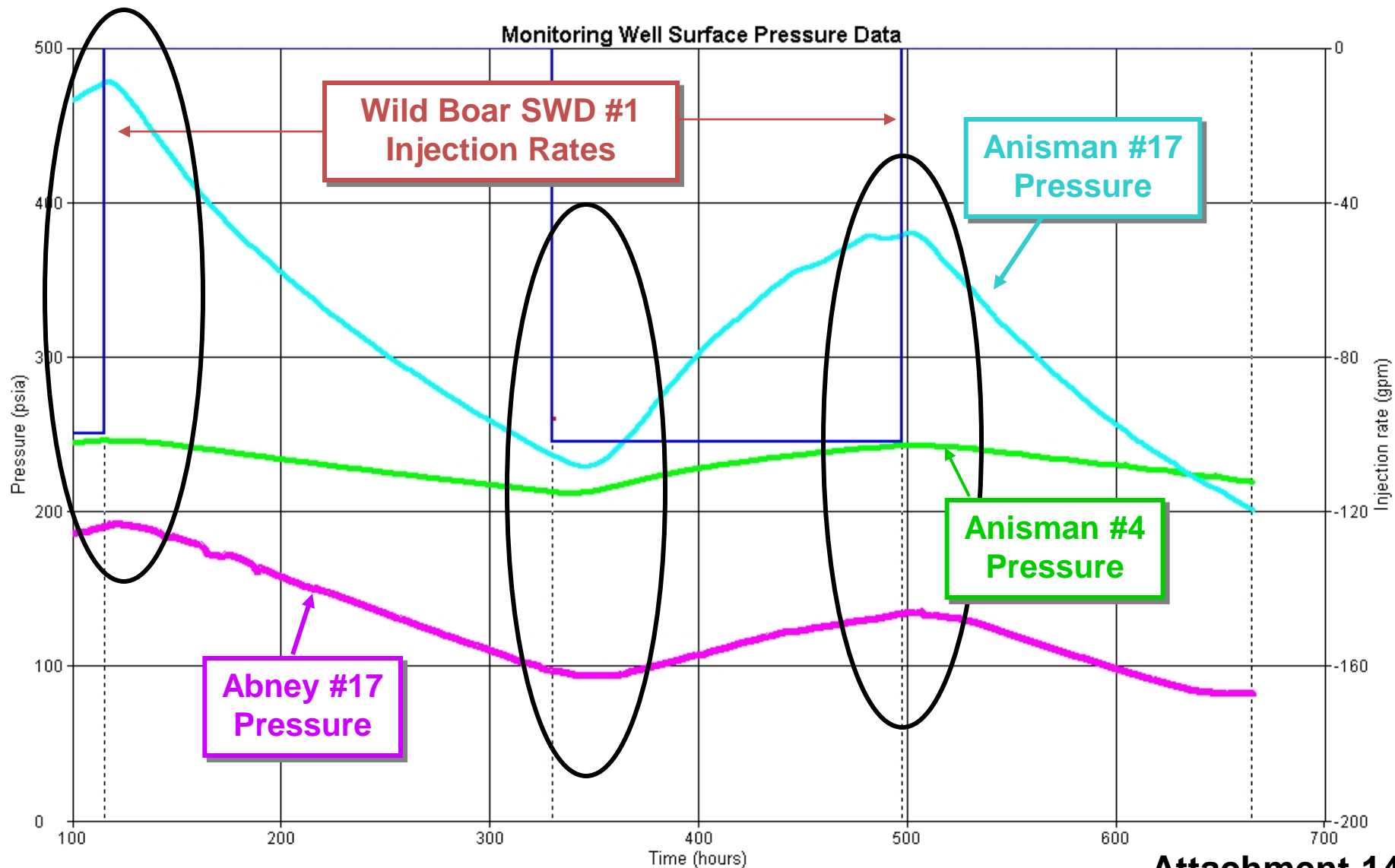
**Stabilization  
Period**

**Injection  
Period**

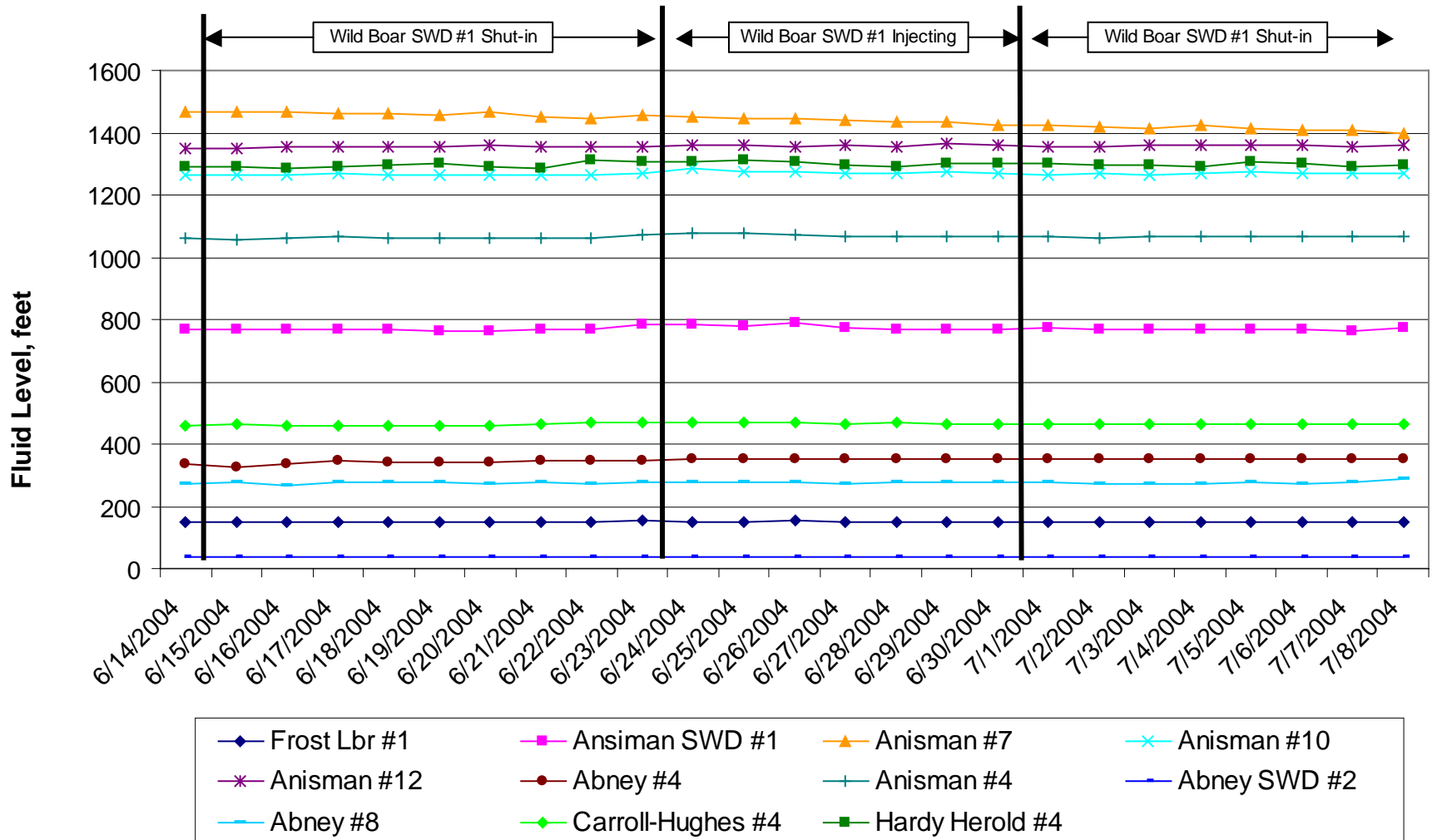
**Falloff  
Period**



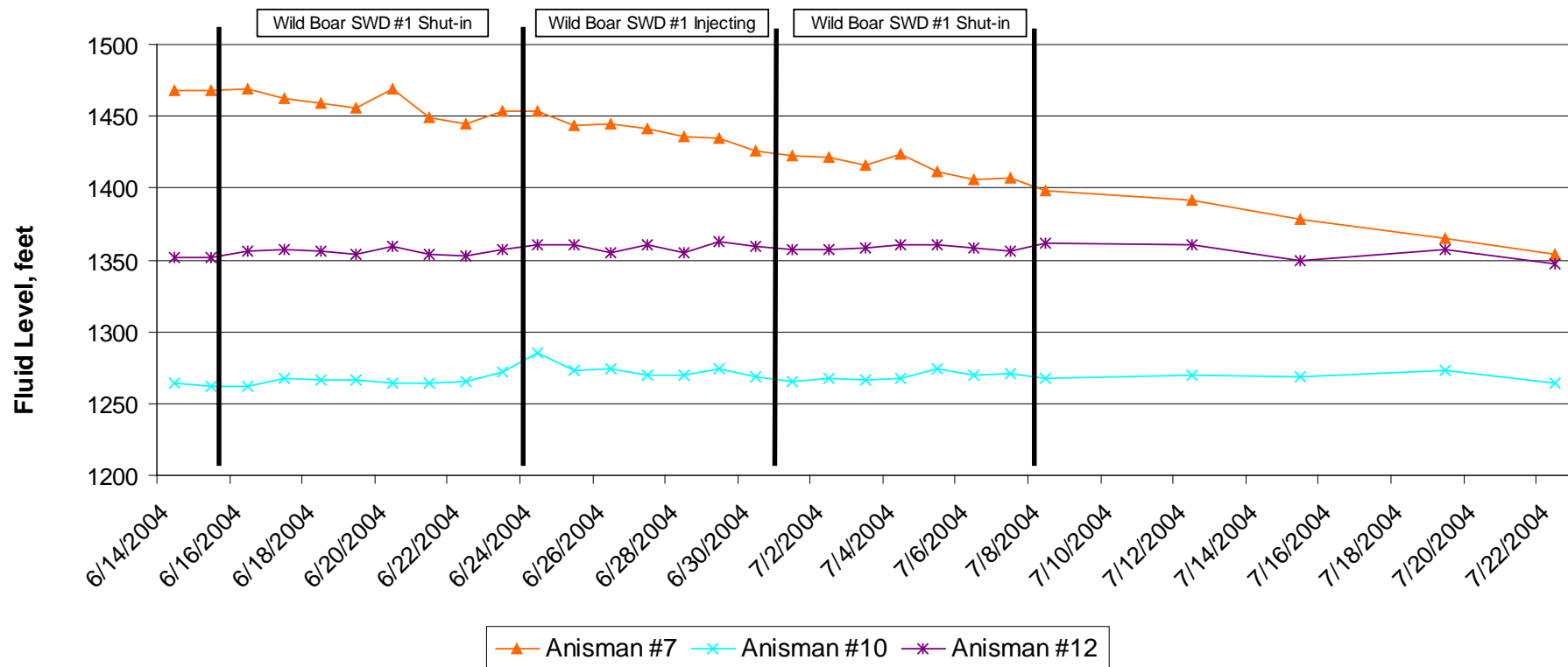
**Time lag between Wild Boar rate change and pressure change**



## Interference Test Fluid Levels

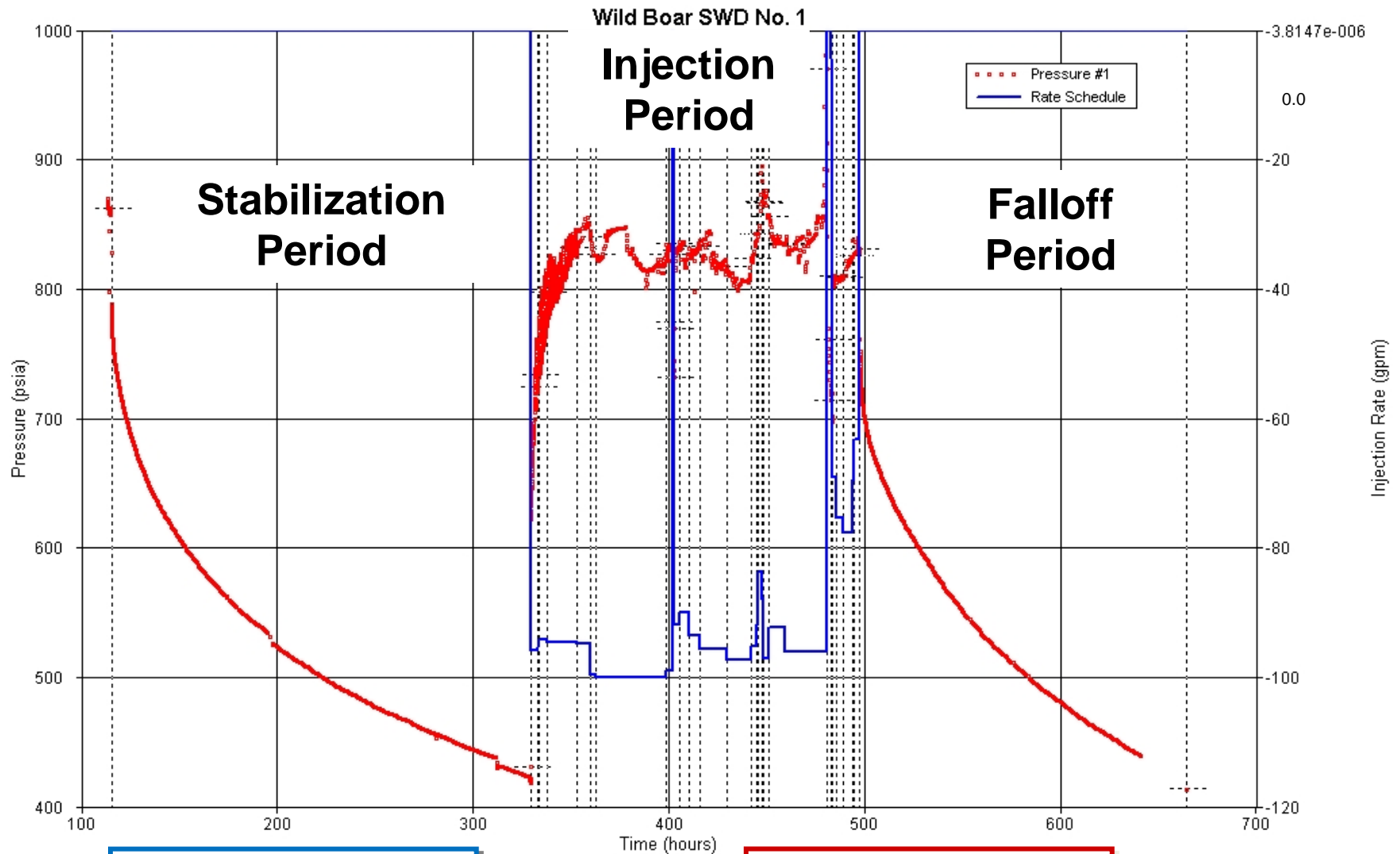


## Interference Test Fluid Levels





# Wild Boar SWD # 1 Measured Injection Rates and Pressure Responses

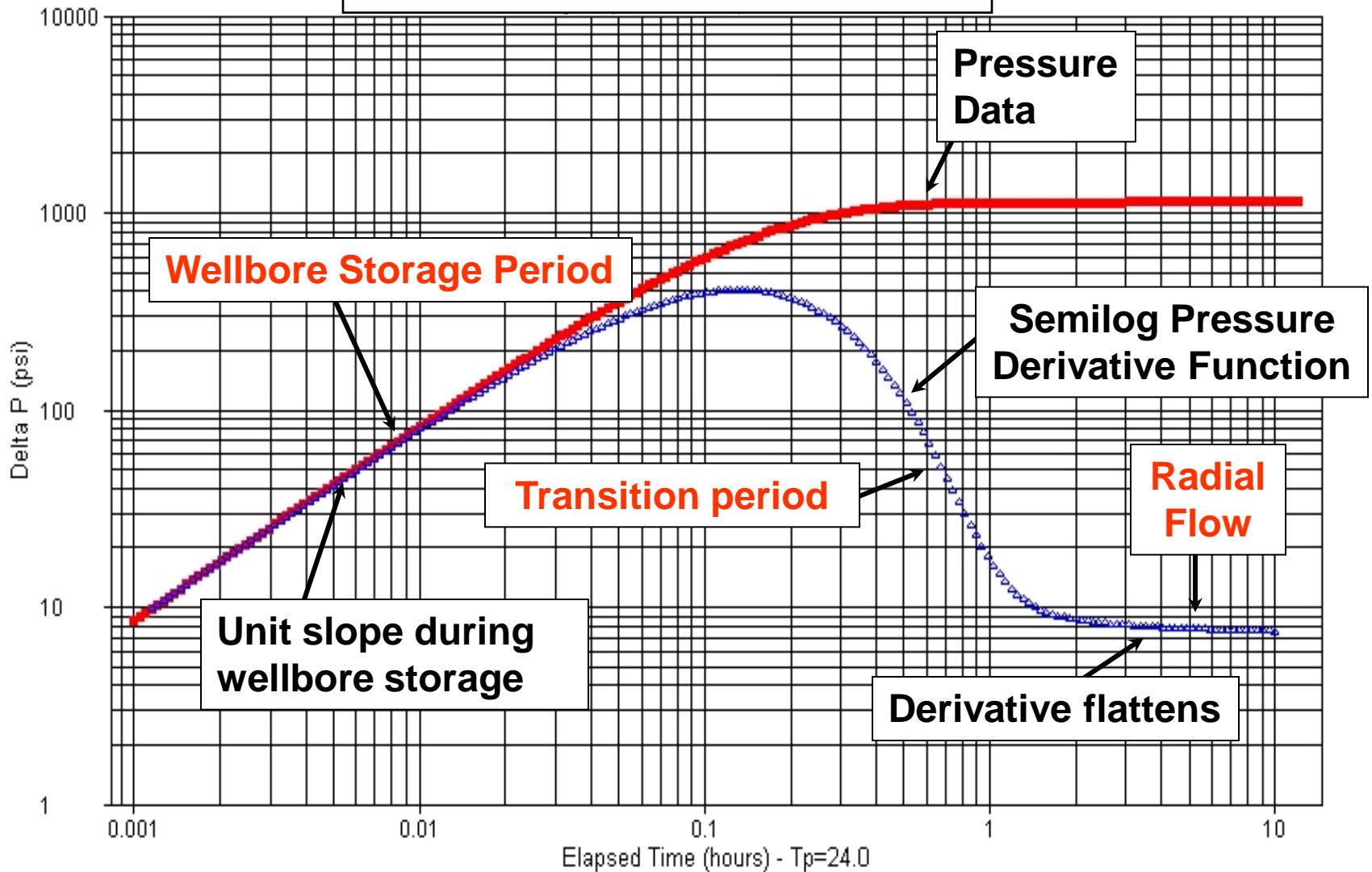


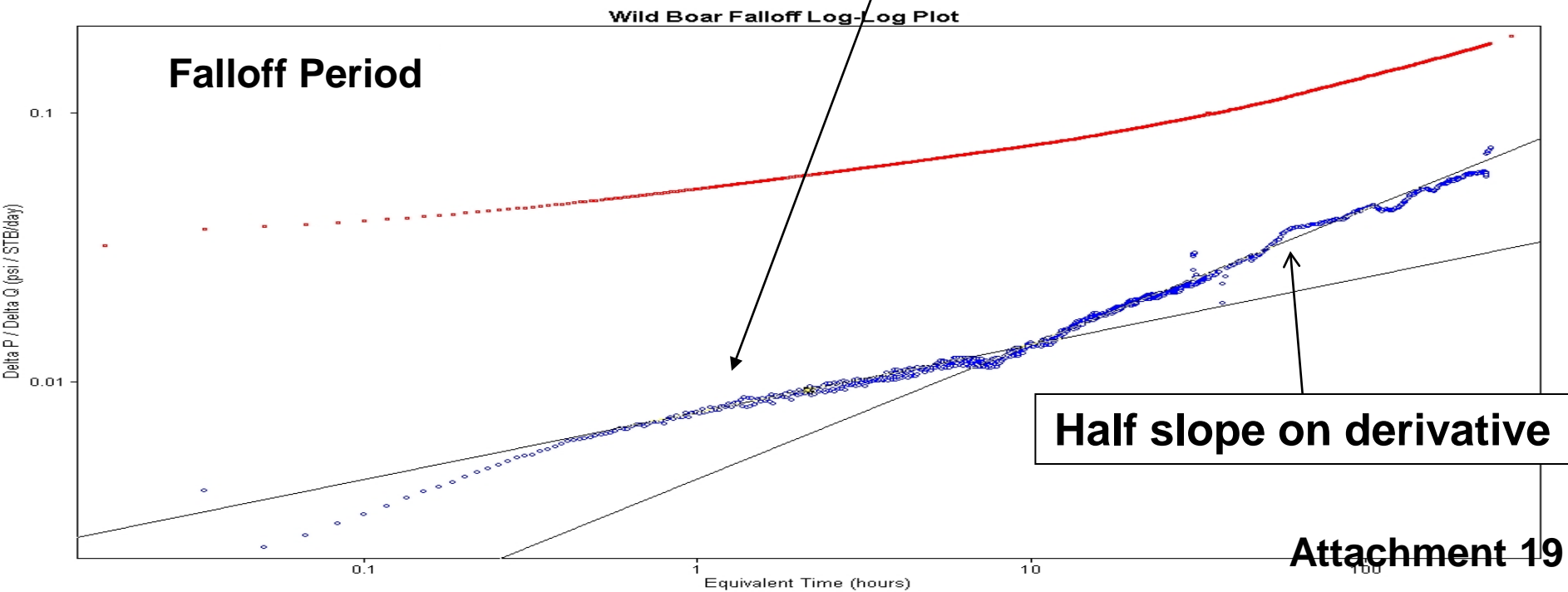
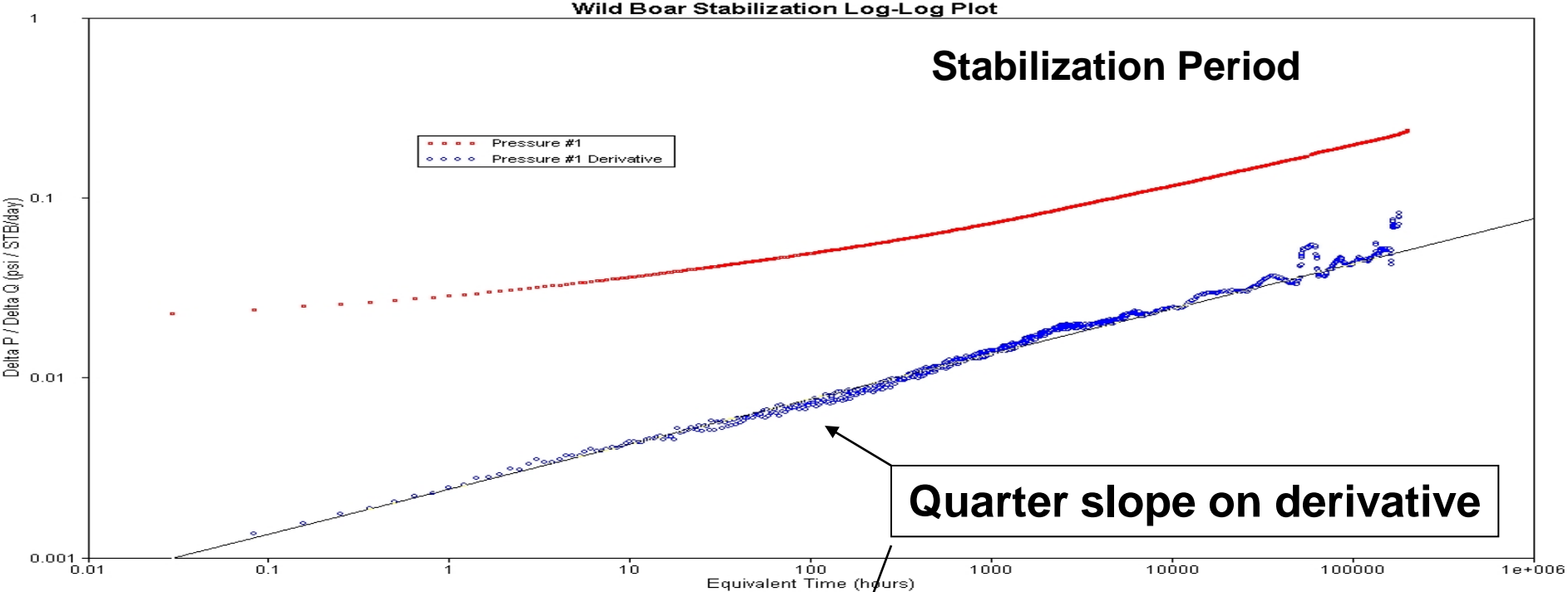
**Wild Boar SWD #1**  
**Injection Rate**

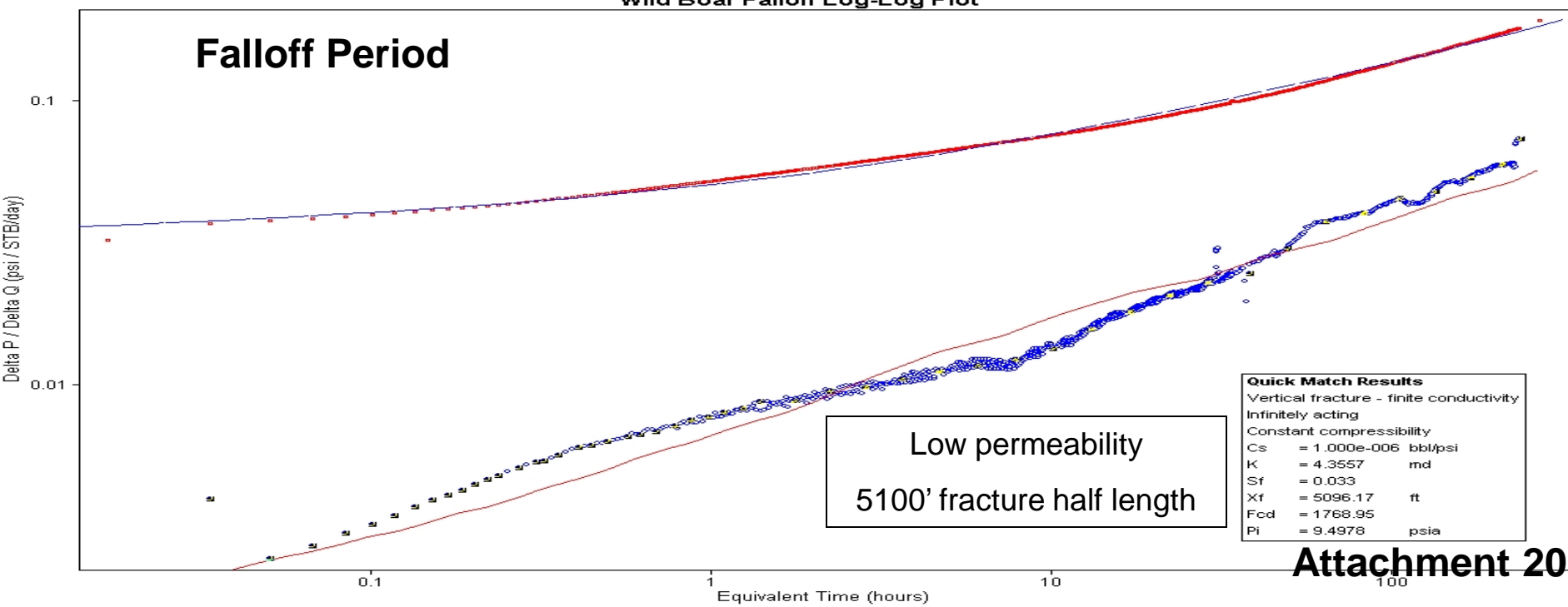
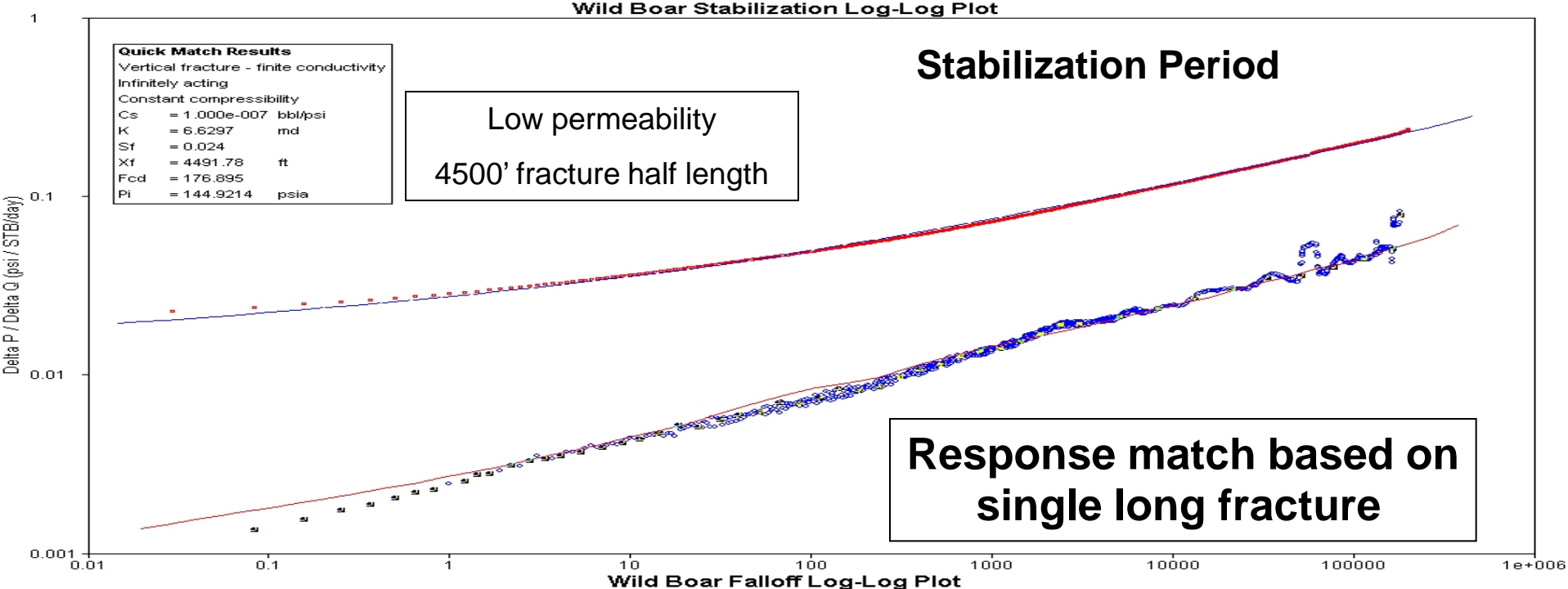
**Wild Boar SWD #1**  
**Pressure**



## Example Log-log Plot



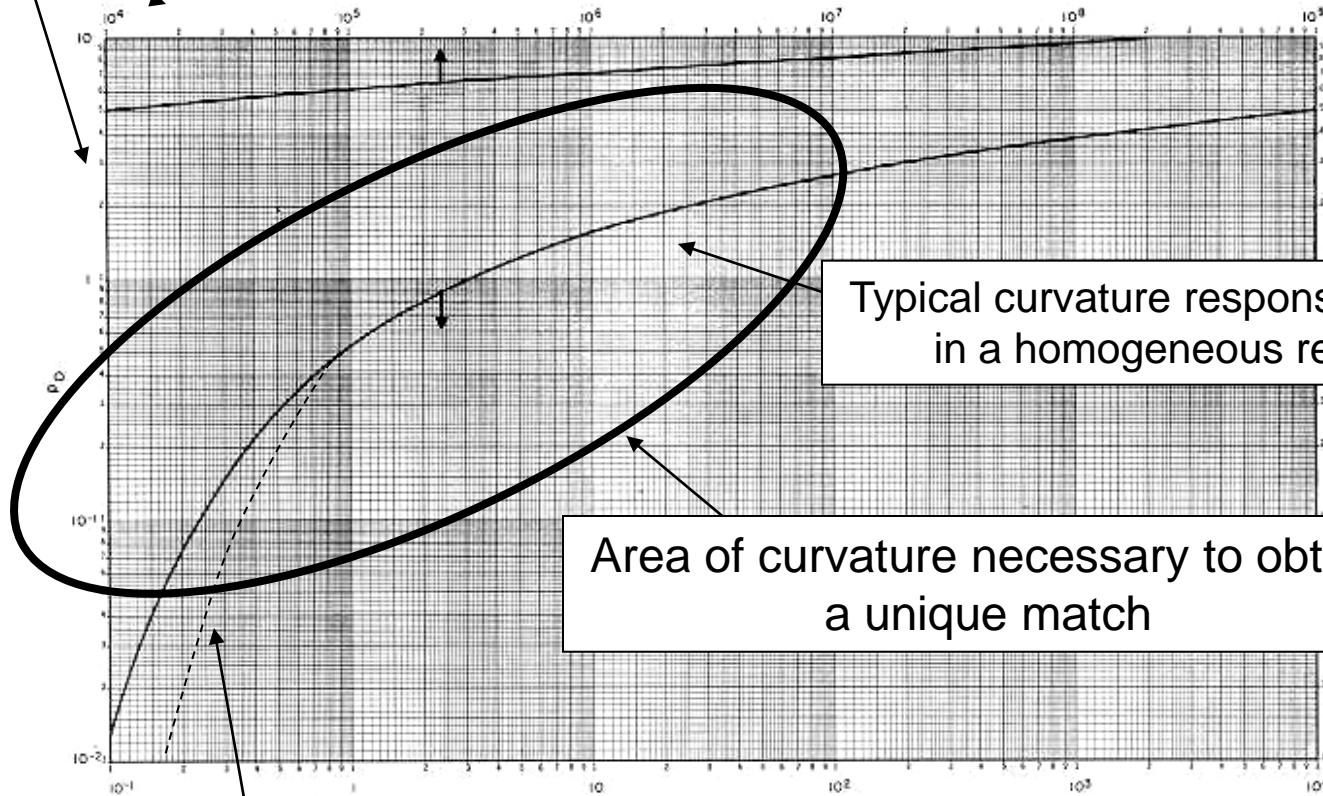




# Ei Type Curve: Figure C.3 from SPE Monograph 5

Log-Log Plot

Dimensionless Pressure



Typical curvature response observed in a homogeneous reservoir

Area of curvature necessary to obtain a unique match

Dimensionless Time Function

A naturally fractured reservoir or a reservoir with directional permeability will have a different early time curvature response

# Type Curve Plot

## Anisman No. 4 pressure interference response during Wild Boar falloff period

**Match Results**  
Radial homogeneous  
Infinitely acting  
K = 21367.7695 md  
OCt = 6.700e-005 psi-1

**Match results: k = 21 d**

Delta P / Delta Q (psi / STB/day)

**Type curve matched to middle time response data**

**Response more rapid than Ei type curve model**

0.1

1

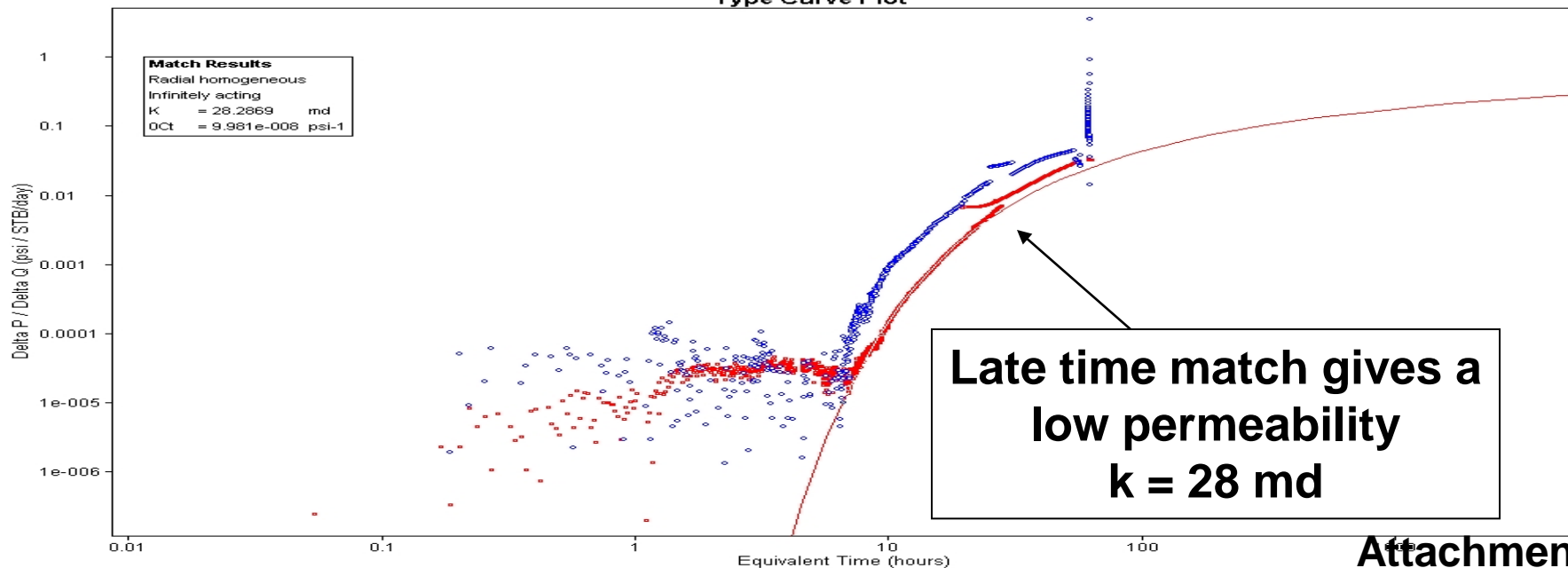
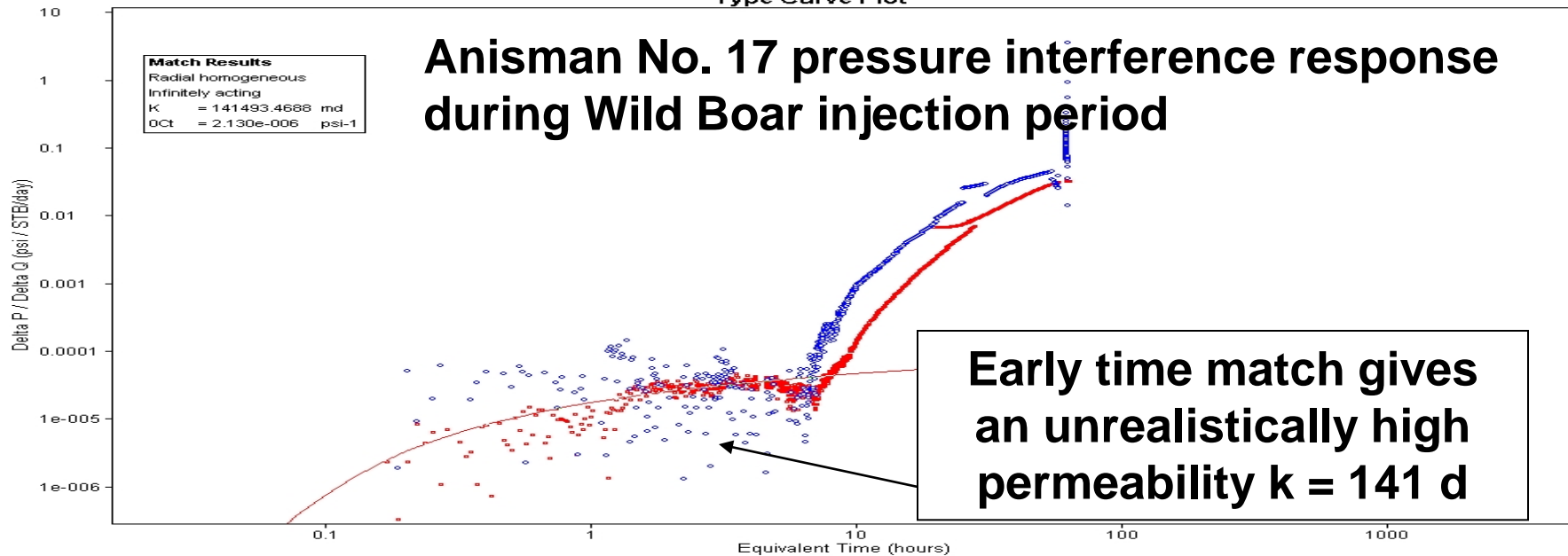
10

100

1000

Equivalent Time (hours)

# Anisman No. 17 pressure interference response during Wild Boar injection period



# Abney No. 17 pressure interference response during Wild Boar stabilization period

**Match Results**

Radial homogeneous

Infinitely acting

K = 488.5858 md

OCt = 3.818e-005 psi-1

Response deviates from Ei type curve

 $\Delta P / \Delta Q$  (psi / STB/day)

1

0.1

0.01

0.001

0.0001

1e-005

1e-006

0.001

0.01

0.1

1

10

100

1000

10000

100000

1e+006

Equivalent Time (hours)

## APPENDIX J: PARADOX VALLEY, COLORADO

The U.S. Bureau of Reclamation runs a deep, high pressure, Class V disposal well in Paradox Valley, Colorado. This operation is part of the Colorado River Basin Salinity Control Project to remove near surface brine and limit saline flow into the Dolores River. Disposal is into the Mississippian carbonate and the upper Precambrian granite. A ten station seismic network was installed in the area prior to well completion. Upgrades are made to the seismic network and the coverage area is enlarged as necessary.

Only one earthquake was recorded prior to injection starting in 1991. Numerous earthquakes followed the start-up of disposal operations. In response to earthquake frequency and magnitude (3.5 and 4.3), the injection rate was reduced in 2000. This method was effective in reducing the frequency. However, in 2010, an increase in low magnitude earthquakes occurred in the northern area, more than 10 km from the well. Since 2000, the near-well seismicity rate has gone up and down in response to variations in long-term averaged injection pressures, but the seismic event frequency remains below pre-2000 levels. The occurrence of earthquakes sufficiently large to be felt (M2.5+) has persisted, however.

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FIGURE J-1: INJECTION-INDUCED SEISMICITY

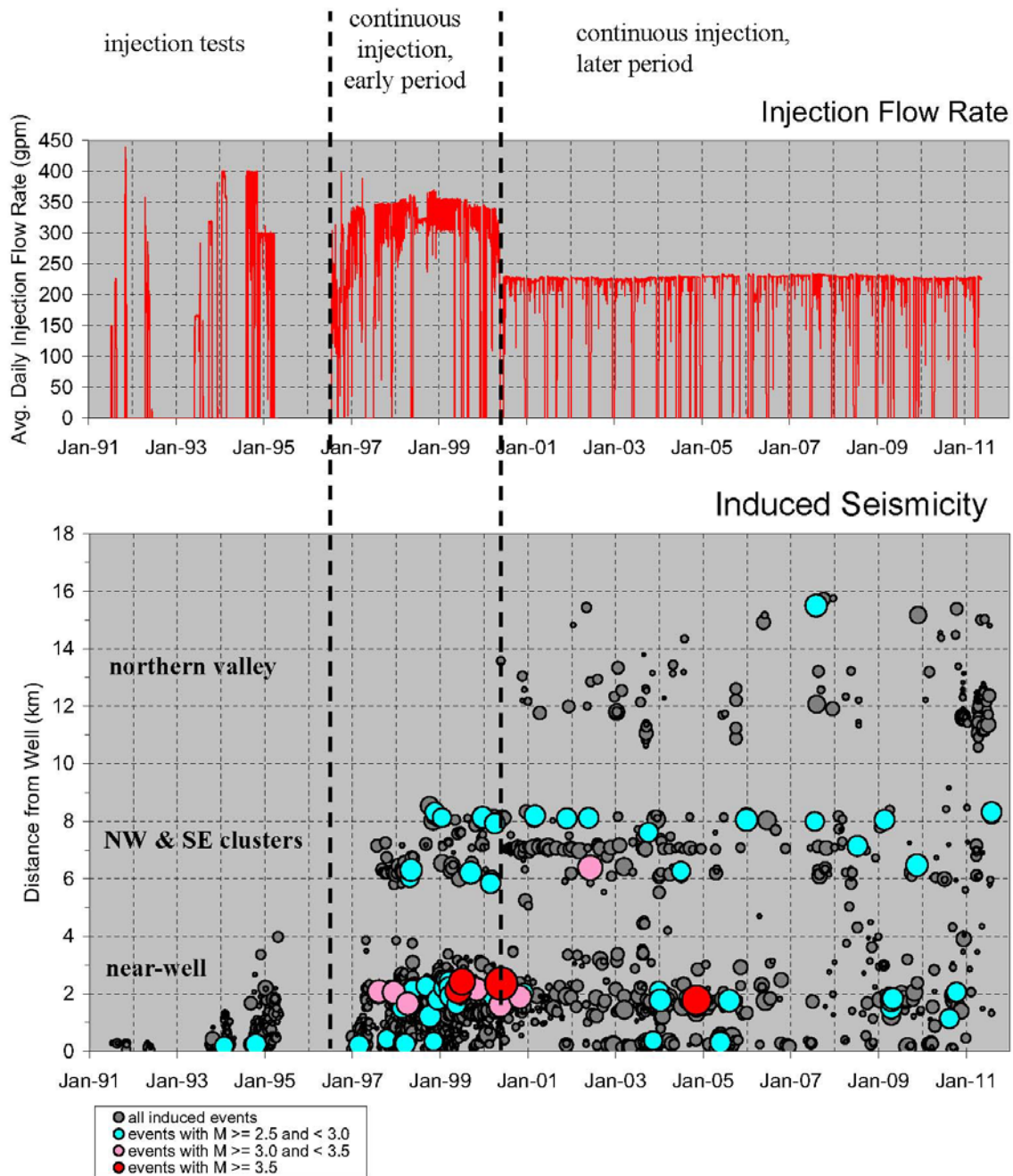
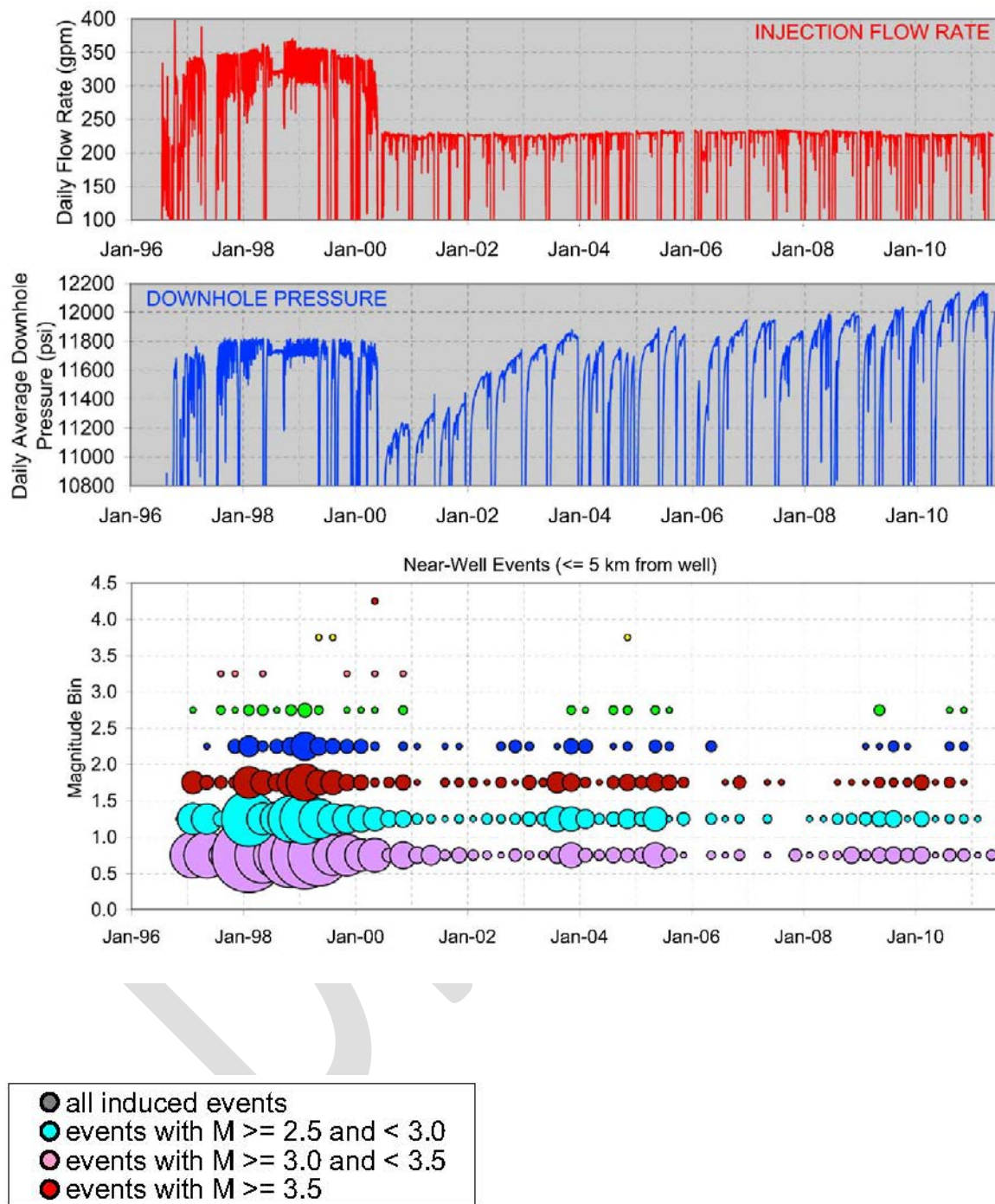


FIGURE J-2: NEAR WELL SEISMICITY



## APPENDIX K: SUBJECT BIBLIOGRAPHY

|  |      |
|--|------|
| Educational Websites.....                        | K-1  |
| General Information and Protocols .....          | K-1  |
| Geothermal .....                                 | K-2  |
| Induced Seismicity Report Four Case Studies..... | K-3  |
| Arkansas Case Studies.....                       | K-3  |
| Fort Worth Basin Case Studies and Geology .....  | K-4  |
| Ohio.....  | K-5  |
| West Virginia.....                               | K-5  |
| Other Induced Earthquake Studies.....            | K-6  |
| Colorado.....                                    | K-6  |
| Production Case Studies .....                    | K-7  |
| Protocols or Risk Analysis .....                 | K-8  |
| Technical or Technology .....                    | K-9  |
| Hydraulic Fracturing or Microseismicity.....     | K-13 |
| Sequestration of CO <sub>2</sub> .....           | K-14 |

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<http://tremor.nmt.edu/>

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<http://www.teachingboxes.org/earthquakes/index.jsp>

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## APPENDIX L: DATABASE INFORMATION

### *CATALOGS OF EARTHQUAKE EVENTS*

The largest U.S. database of earthquake events is maintained by the Advanced National Seismic System (ANSS). The National Earthquake Information Center (NEIC) maintains several other data catalogs. Both ANSS and NEIC programs are under the USGS. There is limited consistency between the various groups on coverage areas, detection thresholds, or magnitude determinations. Table L-2 provides a reference to the primary earthquake catalogs. State Geologic Agencies and universities may also collect and/or host earthquake information on their website. The catalogs generally include an indication of the event location reliability. The main ANSS composite catalog, hosted by the Northern California Earthquake Center at Berkeley, contains events from multiple sources and time periods, but strips duplicate listings.

As an example of catalog coverage, the following table shows the number of events recorded in the search area of the Central Arkansas Area Case Study (discussed in detail elsewhere in this report). Care must be taken to avoid duplication when using multiple sources of data. Not all matching events have the same calculated epicenter and depth. It is also noted that depth refinements to preliminary NEIC data, have been incorporated in the ANSS catalog, but not in the NEIC PDE catalog.

TABLE L-1: EARTHQUAKE CATALOG EVENTS FOR CENTRAL ARKANSAS CASE STUDY

| Catalog   | Common Events with ANSS | Unique Catalog Events | Total Events |
|---|-------------------------|-----------------------|--------------|
| ANSS: Central and Eastern US                                | -                       | 1533                  | 1533         |
| NEIC: SRA <sup>19</sup>                                     | 0                       | 0                     | 0            |
| National Center for Earthquake Engineering Research (NCEER) | 15                      | 1                     | 16           |
| NEIC: USHS <sup>20</sup>                                    | 1                       | 0                     | 1            |
| Center for Earthquake Research and Information (CERI)       | 1523                    | 4                     | 1527         |
| NEIC: PDE & PDE-Q   | 267                     | 12                    | 279          |
| Total unique AR events                                      |                         | 1549                  |              |

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<sup>19</sup> Eastern, Central and Mountain States of U.S. (1350-1986)

<sup>20</sup> Significant U.S. Earthquakes (1568-1989)

TABLE L-2: EARTHQUAKE CATALOGS

| Source  | Coverage (Years)              | Area  | Comments/Caveats  |
|---|-------------------------------|---|---|
| International Seismological Centre <sup>21</sup>                    | 1904- present                 | The official world catalog                                | Requires an access fee                                    |
| ANSS Catalog <sup>22</sup> (hosted by NCEDC)                        | 1898 - present                | Composite across the USA                                  | M1 and greater  |
| CERI Catalog AKA<br>New Madrid Earthquake Catalog <sup>23</sup>     | 1974 - present                | New Madrid Seismic Zone and<br>surrounding regions        |   |
| NEIC (USGS) Catalog <sup>24</sup>                                   | SRA: 1350-1986                | Eastern, Central & Mountain States                        | Very few magnitudes given                                 |
|   | USHIS: 1568-1989              | Significant US quakes                                     | Felt or M4.5 and greater                                  |
|   | PDE: 1973- present            | USA   | Updated file from PDE-Q                                   |
|   | PDE-Q: 1973- present          | USA (most recent)   | Very preliminary locations                                |
|   | Real Time: Last 7 days        | USA   | >= M1; interactive map locations ; with<br>accuracy range |
|   | Alert: current                | USA and World   | E-mail notification available                             |
| NCEER Catalog <sup>25</sup>   | 1627 - 1985                   | Central and Eastern United States                         | Used in national hazard map creation                      |
| ANF/ANFR <sup>26</sup>  | 2009 - present                | US Array Network  | Contains many surface induced events                      |
| IRIS <sup>27</sup> SeismiQuery                                      | 1960 - present                | US & world  | USGS and other networks                                   |
| Harvard CMT Catalog   | 1976 - present                | Global  | Tensor calculations for > M5                              |
| Northern California Earthquake<br>Data Center (NCEDC) <sup>28</sup> | 1910 - 2003<br>1967 - present | Northern and Central CA; some all of CA<br>or Western USA |   |
| Southern California Earthquake<br>Data Center (SCEDC) <sup>29</sup> | 1977 - present                | Southern CA   |   |

<sup>21</sup> ISC: <http://www.isc.ac.uk/search/bulletin/index.html>

<sup>22</sup> ANSS: <http://quake.geo.berkeley.edu/cnss/>

<sup>23</sup> CERI/New Madrid Catalog: [http://www.ceri.memphis.edu/seismic/catalogs/cat\\_nm.html](http://www.ceri.memphis.edu/seismic/catalogs/cat_nm.html)

<sup>24</sup> NEIC: <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>

<sup>25</sup> NCEER: [http://www.ceri.memphis.edu/seismic/catalogs/cat\\_nceer.html](http://www.ceri.memphis.edu/seismic/catalogs/cat_nceer.html)

<sup>26</sup> IRIS EarthScope Data: <http://www.iris.edu/earthscope/usarray/>

<sup>27</sup> IRIS: <http://www.iris.edu/SeismiQuery/sq-events.htm> & <http://www.iris.edu/dms/wilber.htm>

<sup>28</sup> NCEDC: <http://www.ncedc.org/ncedc/catalog-search.html>

<sup>29</sup> NCEDC: <http://www.data.scec.org/>

## APPENDIX M: USGS COLLABORATION

Through an interagency agreement, EPA was able to employ the expertise of USGS staff for this project as outlined in the scope of work<sup>30</sup> below. USGS prepared a report titled, *Evaluate Potential Risks of Seismic Events due to Injection-Well Activities*. The report included a guide on the USGS earthquake hazards and seismic activity maps aimed at non-geophysicists (UIC scientists and engineers). The report also provided USGS insight on the relationship between subsurface stress fields and the likelihood of induced seismicity.

USGS is updating the 2002 study, *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001*<sup>31</sup>. Table M-1 provides a summary of the seismic events reported in ANSS catalog for the greater Raton Basin Area located in southern Colorado and northern New Mexico as shown in Figure M-1. The area has a number of disposal wells used to inject the wastewater from coalbed methane production. The USGS report, to be completed by April 2012, will provide refined locations and interpretation of many of these events.

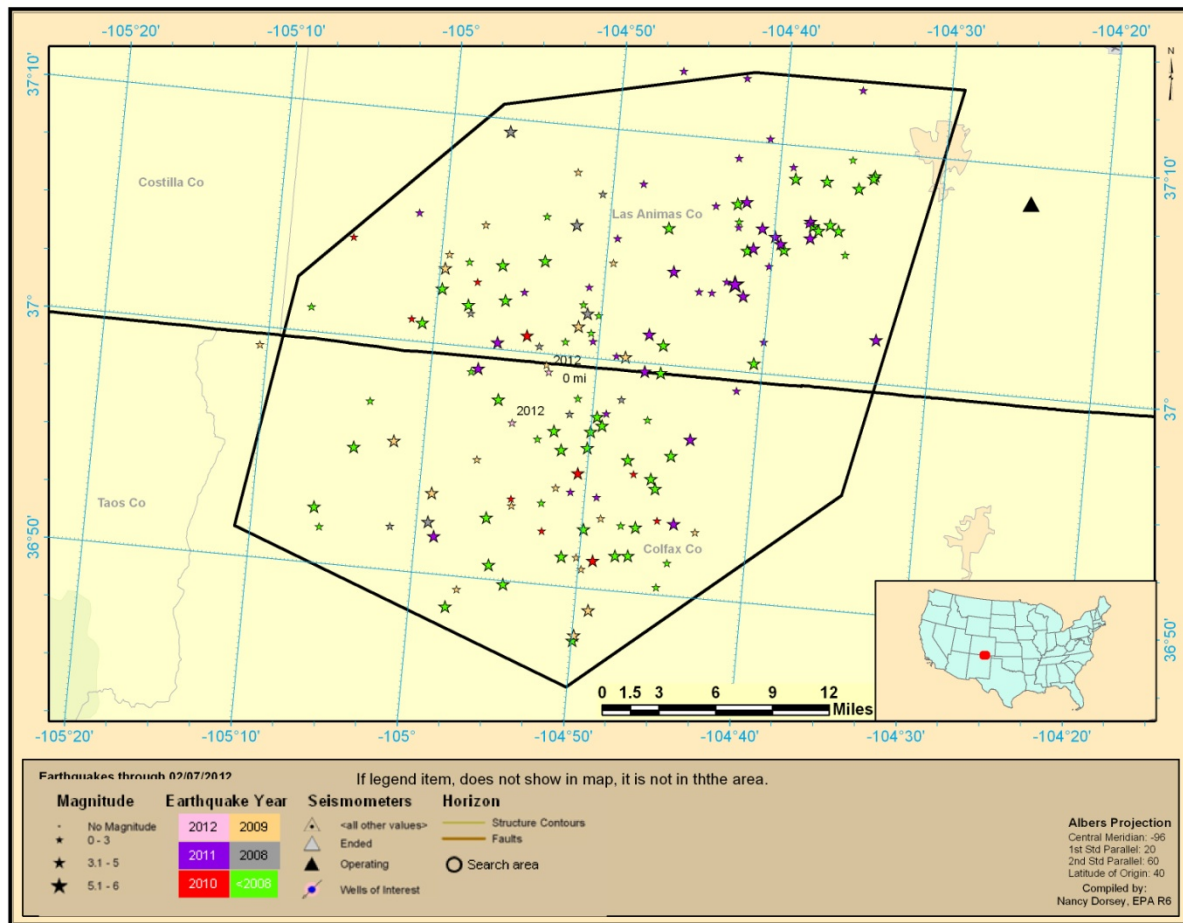
TABLE M-1: SEISMIC EVENTS IN THE RATON BASIN AREA

| Year | Starting Date | Number of Events | Min. | Avg. | Max. | Ending Date |
|------|---------------|------------------|------|------|------|-------------|
| 1973 | 9/19/1973     | 1                | 0.0  | 2.1  | 4.2  | 9/23/1973   |
|      |               |                  |      |      |      |             |
| 2001 | 8/28/2001     | 13               | 2.8  | 3.5  | 4.5  | 12/15/2001  |
| 2002 | 1/26/2002     | 4                | 2.8  | 3.2  | 3.5  | 11/14/2002  |
| 2003 | 4/28/2003     | 7                | 2.9  | 3.4  | 3.8  | 11/24/2003  |
| 2004 | 1/14/2004     | 8                | 2.9  | 3.5  | 4.4  | 8/1/2004    |
| 2005 | 1/10/2005     | 10               | 2.9  | 3.4  | 5.0  | 11/16/2005  |
| 2006 | 1/27/2006     | 13               | 2.5  | 3.0  | 3.6  | 12/24/2006  |
| 2007 | 1/3/2007      | 7                | 2.6  | 3.3  | 4.4  | 12/17/2007  |
| 2008 | 1/29/2008     | 10               | 2.5  | 2.9  | 3.4  | 9/6/2008    |
| 2009 | 2/3/2009      | 20               | 2.5  | 3.0  | 4.1  | 12/11/2009  |
| 2010 | 1/18/2010     | 10               | 2.5  | 3.0  | 3.8  | 11/10/2010  |
| 2011 | 2/13/2011     | 40               | 0.0  | 3.1  | 5.4  | 12/28/2011  |
| 2012 | 1/25/2012     | 2                | 2.4  | 2.5  | 2.6  | 1/29/2012   |

<sup>30</sup> Task 3 was dropped from the scope of work. The timeframe for Task 4 has been extended.

<sup>31</sup> Meremonte, M. E., J. C. Lahr, A. D. Frankel, J. W. Dewey, A. J. Crone, D. E. Overturf, D. L. Carver, and W.T. Bice, 2002, *Investigation of an Earthquake Swarm near Trinidad, Colorado, August-October 2001*: US Geological Survey Open-File Report 02-0073 [<http://pubs.usgs.gov/of/2002/ofr-02-0073/ofr-02-0073.html>], accessed December 5, 2011.

FIGURE M-1: TRINIDAD AND RATON BASIN SEISMICITY



# Scope of Work for USGS and EPA Project on Induced Seismic Activity for Class II Disposal Wells

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**Objective:** Provide support data for EPA's UIC National Technical work group project on induced seismicity from Class II brine disposal well operations.

**Background:** Numerous publications exist that study the relationship between induced or triggered earthquakes and injection activity. The factors that might influence the occurrence of large damaging earthquakes near Class II disposal wells include (1) large-scale nearby fault(s), (2) high differential stresses at depth, and (3) changes in fluid pressure or stress due to fluid injection. In light of the recent earthquake events in Arkansas and Texas, the UIC National Technical Workgroup (NTW) will develop technical recommendations to enhance strategies for avoiding damaging seismicity events related to Class II disposal wells.

**Scope of Work:** Through available expertise, complete the following specific work tasks that support the UIC NTW induced seismicity project. USGS and/or procured data will be used and referenced in the UIC NTW final work product. The tasks will necessitate cooperation between EPA and USGS, including incorporating the expertise and experience from EPA UIC geologists and engineers and USGS staff.

## Work Tasks

1. Prepare a practical guide on the USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers (non-geophysicists). The document should cover topics such as background information relevant to the two maps, confidence levels and sensitivity of the mapped data. For example:
  - a. Describe the epicenter location and hypocentral depth with respect to accuracy of the data. This should include accuracy within both map and depth locations.
  - b. Describe the relevance of the earthquake hazard maps for subsurface use.
2. Using technical expertise what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?
3. Incrementally evaluate commercial structure maps on the deepest available horizon for one of the following areas to determine if this type of data can be used as a screening tool. EPA will provide USGS with the structure maps. The evaluation may include, but is not limited to, correlating seismic events and available injection well locations with structural maps. During coordination between EPA and USGS, specific location information will be provided. The following are the generic areas of interest, though EPA may change the priorities.
  - a. North Texas Ouachita Thrust front
  - b. Arkansas Fayetteville Shale play
  - c. West Virginia Braxton County
  - d. Colorado Trinidad area
  - e. Ashtabula Ohio area

Depending on the results of the initial pilot study, additional analyses may be performed on more of these areas at a later date.

4. Review *Investigation of an Earthquake Swarm near Trinidad, Colorado Aug-Oct 2001* and submit a progress report and final report on updates to this study including identifiers that could have predicted the recent 5.3 earthquake.
5. Provide interim data, final report of conclusions and all work completed.

## **Milestones**

Provide monthly updates

## **Timeframe**

Work and accompanying reports for tasks 1-3 should be completed by December 16, 2011.

A progress report for task 4 should be completed by December 31, 2011, with work on task 4 continuing into 2012. The final report for task 4 should be completed no later than April 30, 2012.

## **Evaluate Potential Risks of Seismic Events due to Injection-Well Activities**

A. McGarr, W. Ellsworth, J. Rubinstein, S. Hickman, E. Roeloffs, and D. Oppenheimer

United States Geological Survey

The Scope of Work for the USGS and EPA project on induced seismic activity for Class II disposal wells includes two tasks:

Task 1—Prepare a practical guide on USGS earthquake hazards and seismic activity maps aimed at UIC scientists and engineers.

Task 2—Using technical expertise, what is the likelihood of estimating deep stress fields from surface or airborne geophysical data?

The results of USGS work on these two tasks are described in this report.

# Task 1.

## USGS Data Products for Earthquake Hazards

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### Earthquake Catalog—ANSS Earthquake Catalog

<http://www.quake.geo.berkeley.edu/anss/>

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This is the authoritative earthquake catalog for the United States. It contains the most current information from all of the participating regional networks and the U.S. National Network in the Advanced National Seismic System (ANSS). This catalog can be searched for a given geometric area, over a given time and a given magnitude range. Quarry blasts and earthquakes can also be selected/deselected. Earthquake time, location, magnitude, magnitude type, and parameters relating to how the earthquake location and magnitude were computed (number of stations, travel time error, and source network) are contained in the output of this search. This catalog contains all earthquakes that were detected by the local and regional networks within the United States, including both natural and induced earthquakes—if quarry blasts are not turned off, they will be included as well. This catalog reflects historical seismicity, which may be used as a guide to where we expect future seismicity, but there is always a possibility that earthquakes will occur where previous earthquakes have not. The catalog can be searched for earthquake-specific areas using the search tools at <http://www.ncedc.org/anss/catalog-search.html>. This catalog is updated in near-real time.

#### *Caveats*

- This earthquake catalog is not uniform. In some regions, the catalog begins much earlier than in others, because seismometers were deployed earlier.
- Detection capabilities are not uniform. As a seismic network becomes denser with time, it is able to record smaller earthquakes. This also means that regions with dense networks will see smaller earthquakes than regions with more sparse seismic networks.
- Earthquake locations and magnitudes are of varying quality. As the number of instruments close to the earthquakes increases, location and magnitude estimates become more accurate. This means that location and magnitude quality vary from region to region. Location and magnitude quality also vary over time within a region as the number of instruments increase.
- Earthquake magnitudes are computed a number of different ways depending on the earthquake size and number of nearby stations. These magnitudes are often similar, but not always the same.
- ANSS also maintains a webpage with caveats about their catalog:  
<http://www.ncedc.org/anss/anss-caveats.html>



An example of how increasing station density improves earthquake detection is found at the end of this document in the **USArray** section.

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### **Earthquake Databases**

<http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>

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A variety of additional earthquake catalogs covering the U.S. are available online and can be used to search for both recent and historical earthquakes. An introduction to earthquake databases and catalog sources is available at <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/database.php>. Special attention should be paid to the explanation of differences between the various catalogs.

Online search tools that can be customized to select earthquakes in different geographic regions and over different time and magnitude ranges are available at <http://earthquake.usgs.gov/earthquakes/eqarchives/epic/>.

#### *Caveats*

- These earthquake catalogs are not uniform in either space or time. In some regions, the catalog begins much earlier than in others because seismometers were deployed earlier.
- Earthquake smaller than magnitude 1 are not included in these catalogs.
- In most areas, the catalog is complete since 1973 for earthquakes of magnitude 3 or larger.
- The accuracy of the earthquake locations varies considerably. In most areas outside of California, Nevada, Oregon, Washington, and Utah, earthquake epicenters may be in error by as much as 6 miles, on average. Exceptions apply where there are local networks, such as in the New Madrid Seismic Zone.

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### **National Seismic Hazard Map**

<http://earthquake.usgs.gov/hazards/products/>

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The National Seismic Hazard Map delineates the probability of strong shaking across the United States from natural earthquakes. These maps do not assess the risk of shaking owing to induced earthquakes. These are probabilistic maps and do not refer to specific earthquakes. Instead, the maps provide information on the strength of earthquake shaking that is unlikely to be exceeded over a given period of time.

A guide to the hazard maps can be found at:  
<http://earthquake.usgs.gov/hazards/about/basics.php>

Frequently Asked Questions about Hazard Maps:  
<http://earthquake.usgs.gov/learn/faq/?categoryID=27>

The maps are derived from knowledge of active faults, past earthquakes, and information on how seismic waves travel through the Earth. As indicated above, our knowledge of past earthquakes and faults is incomplete, which means that strong shaking due to earthquakes may still occur in regions with low probabilities. It is less likely to occur in these regions, but it still can happen.

The ground motions reported in these maps are estimated for the surface. Ground motions decrease with depth below the surface. Shaking is strongest in the area immediately surrounding an earthquake.

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### **Earthquake Probability Calculator**

<https://geohazards.usgs.gov/eqprob/2009/index.php>

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This tool allows you to compute the probability of an earthquake occurring within a specific radius of a specified location. The probabilities are derived from the National Seismic Hazard Map described above. The tool produces two products:

1. A map surrounding the location specified, with color contours giving the probabilities of an earthquake larger than or equal to the magnitude specified by the user (minimum magnitude 5.0)
2. An optional text report describing the annual rates of earthquakes of different sizes.

It is important to note that, where the probability on the maps is shown to be 0.00, this does not mean that there will not be an earthquake there. When a region falls into the 0.00 category, it means that the probability of an earthquake is less than 1% during the time period specified.

By selecting the Text Report, it is possible to change the radius from the default value of 50 km. The Text Report gives information for earthquakes that fall within magnitude bins (for example, between 7.35 and 7.45): the annual rate at which an earthquake in that bin is expected to occur, the annual rate at which an earthquake within that bin or larger will occur, and probabilities of an event within that magnitude bin and within that bin or larger occurring in the time period specified by the user. The last two quantities can be inverted to determine the average number of years between earthquakes.

### *Limitations of the Probability Mapping Calculation*

The probability is only calculated for events of M5 and larger. It is advisable to consider the rates of smaller earthquakes that may be the first evidence that an area is sensitive to injection-induced earthquakes. Such a calculation can be done using catalog searches but is not currently available as an online tool.

There are no confidence intervals on the probabilities. The values given are annual averages and earthquake rates naturally fluctuate in time. Therefore, as presently written, this application cannot help decide whether the seismicity in the last year, for example, is within the normal range of variation for this site.

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### **The Quaternary Fault and Fold Database of the United States**

<http://earthquake.usgs.gov/hazards/qfaults/>

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This database contains information on known faults and associated folds in the United States that are believed to have been sources of  $M > 6$  earthquakes during the Quaternary (the past 1,600,000 years). The website includes both static and interactive maps of these geologic structures, with links to detailed references.

This database does not include faults that show no evidence of Quaternary movement. Faults that have had  $M > 6$  earthquakes but that do not extend to the surface and/or that have not been recognized at the surface may not be in the database. Only faults believed capable of hosting  $M > 6$  earthquakes are included, but earthquakes as small as  $M5$  are potentially damaging, especially in the Central and Eastern U.S.

These considerations mean that, if the site is near a fault in the Quaternary Fault and Fold Database, then the necessary geologic structure exists to host an earthquake of  $M > 6$ . However, if no fault in the database is near the site, it does not necessarily mean that no such fault is present.

New faults are continually being discovered, often as they reveal themselves by earthquake activity. Several years or more may pass between initial recognition that a fault is present, documentation in peer-reviewed literature that the fault is aerially extensive enough to produce a significant earthquake, and incorporation of the fault into the database. Changes to the Quaternary fault database are incorporated into the updates to the National Seismic Hazard Maps that occur every 6 years.

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### **USArray—An Example of Improved Detection Capabilities From Increased Station Density**

<http://www.usarray.org/>

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As of this writing, a large seismic array of 400 instruments is moving across the conterminous U.S. This array, called USArray, is operated by the Incorporated Research Institutions for Seismology (IRIS) and is funded by the National Science Foundation as part of the EarthScope Program. During the 18 months that it takes for the USArray to pass by any particular location, the density of seismic stations is temporarily increased to one station approximately every 70 km, placing a seismometer within about 35 km of every point within the footprint of the array. This higher station density makes it possible to detect and locate earthquakes



with  $M \geq 2$  in most areas and provides data that can be used to reduce the location uncertainty.

When USArray was passing through eastern Colorado and New Mexico from late 2008 to early 2010, several hundred events were detected that were not initially identified by the USGS. Many of these earthquakes lie within or near the coal-bed methane field west of Trinidad, CO.

The Oklahoma Geological Survey has recently used data from USArray to study earthquakes in Garvin County, Oklahoma, and their possible association with shale gas stimulation activities in the Eola Field (Holland, 2011). This report illustrates the potential of improved seismic monitoring for answering basic questions about the association between earthquakes and fluid injection activities. It also draws attention to the challenges of drawing firm conclusions when the historical context of the activity is poorly known and poorly resolved. The same general conclusions can be drawn from the study of earthquakes near Dallas-Fort Worth Airport (Frohlich, C., and others, 2011).

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- Holland, A., 2011, Examination of possibly induced seismicity from hydraulic fracturing in the Eola Field, Garvin County, Oklahoma: Oklahoma Geological Survey Open-File Report F1-2011, 31 p.

*The online tools described here are products of the U.S. Geological Survey, but no warranty, expressed or implied, can be provided for the accuracy or completeness of the data contained therein. These tools were not developed for the specific purpose of assessing the potential for induced seismicity and are not substitutes for the technical subject-matter knowledge.*

## **Task 2.**

# **Deep Stress Fields and Earthquakes Induced by Fluid Injection**

#### **Executive Summary**

The purpose here is to explain what we know about deep stress fields and how this might influence the likelihood of earthquakes induced by injection well activities. The available evidence indicates that whether the tectonic setting is active (for example, near the San Andreas Fault in California) or inactive (for example, central or eastern United States), activities that entail injection of fluid at depth have some potential to induce earthquakes. This does not imply, however, that all injection-well activities induce earthquakes or that all earthquakes induced by injection activities are large enough to be of concern. Indeed, most injection wells do not appear

to cause earthquakes of any consequence. The differences between the small percentage of wells that induce noticeable earthquakes and those that cause negligible seismicity are poorly understood. Thus, it is necessary to measure the response of the rock mass to injection to estimate the likelihood that a particular injection well will contribute to the local seismicity. An effective way to do this is seismic monitoring, using local networks that are capable of recording small-magnitude events. Furthermore, to evaluate the likelihood of inducing damaging earthquakes on large-scale, pre-existing faults, information is also needed on the geometry of potentially active faults in relation to the orientations and magnitudes of stresses at depth. This information can be obtained from network observations of ongoing micro-seismicity (if present), borehole stress measurements, and geophysical and geological investigations of fault geometry and fault-slip history.

Even in the absence of detailed information on stresses and fault geometry for a particular site, some useful generalizations can be made on the deep stress field. These generalizations are based on borehole stress measurements made around the world at depths of as much as 8 km, in conjunction with earthquake, geologic, and laboratory studies:

1. The stress field can be described in terms of three principal stresses that are oriented perpendicular to one another. To a good approximation, one of these principal stresses is vertical and the other two are horizontal.
2. The vertical principal stress is readily estimated because, at a given depth, it is due to the weight of the overlying rock mass.
3. The state of stress falls into three categories, depending on the relative magnitudes of the three principal stress regimes: normal, strike-slip, and reverse faulting, for which the vertical principal stress is the maximum, intermediate, or minimum principal stress, respectively. Studies of earthquake focal mechanisms, borehole stress indicators, and active faults have revealed the orientation of the principal crustal stresses at a broad, regional scale over most of the United States.
4. Stress measurements made in boreholes indicate that the horizontal principal stresses generally increase linearly with depth, similarly to the vertical principal stress, but sometimes with significant local perturbations.
5. For a given state of stress and depth, borehole stress measurements are generally consistent with laboratory friction experiments, which suggest that stresses are limited by the strength of the crust.
6. Observations that earthquakes, natural or man-made, may be induced by relatively small stress changes support the idea that the crust is commonly close to a state of failure.

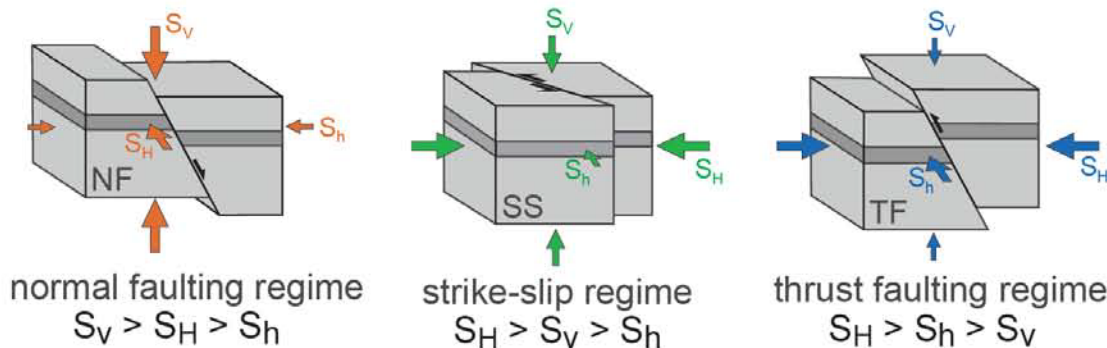
## **Introduction**

Of the approximately 144,000 Class II injection wells in the United States that inject large quantities of brine into the crust, only a small fraction of these wells induce earthquakes that are large enough to be of any consequence. In spite of their small numbers, these few cases raise concerns about the potential for significant damage resulting from larger induced earthquakes. Accordingly, it would be useful to have some guidelines concerning the likelihood that a particular well will cause significant earthquakes. The intent of Task 2 is to investigate the possibility that the deep stress field can be estimated from surface data. If so, then the next question is whether this stress information can be used to estimate the likelihood of substantial induced seismicity.

## State of Stress

From information already available, we know the deep stress field to some extent. The stress field can be described as three principal stress components orthogonal to one another, with one component oriented vertically, perpendicular to the earth's surface, and the other two oriented horizontally. Factors including topography and geologic structure can alter these principal stress directions somewhat, but not on a large scale. The vertical principal stress at a given depth is, to a good approximation, the product of depth, gravity, and the average density between the surface and the point of interest. Because the approximate density structure of the crust is known nearly everywhere, the vertical principal stress can be readily estimated. Estimating the horizontal principal stress magnitudes requires more information, including knowledge of the local tectonic stress regime.

Surface data from seismograph stations or from observations of active faults and other stress indicators can reveal the tectonic stress regime, at least on a regional scale. This stress regime falls into three categories: normal faulting (vertical principal stress is maximum), strike-slip faulting (vertical principal stress is intermediate), or reverse faulting (vertical principal stress is minimum) (fig. 1). Earthquake focal mechanisms determined from ground motion recorded at seismograph stations indicate the stress regime wherever earthquakes occur, and, if properly analyzed, can provide valuable information on stress orientations (for example, Hardebeck and Michael, 2006). Geologic investigations of active faults, as well as geodetic measurements of crustal strain accumulation, provide similar information. Accordingly, from these sorts of investigations, which can be made from the surface, we know the regional tectonic stress



**Figure 1.** Schematic diagram showing tectonic stress regimes and sense of fault offset in relation to the vertical principal stress ( $S_v$ ), the maximum horizontal principal stress ( $S_H$ ), and the minimum horizontal principal stress ( $S_h$ ) (from World Stress Map, cited below).

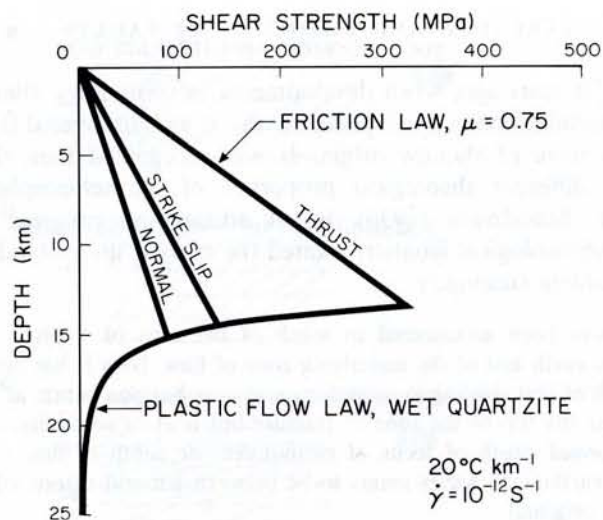
regime nearly everywhere in the United States and for much of the world (see World Stress Map, cited below). However, these observations only tell us the orientations and relative magnitudes of the horizontal principal stresses, and, hence, indicate whether we are in a normal, strike-slip, or reverse faulting stress regime. They do not tell us the absolute magnitudes of the horizontal



stresses, which, together with information on stress orientations, determine proximity to failure on favorably oriented pre-existing faults.

### Magnitudes of Horizontal Stresses

The question of the magnitudes of the horizontal stresses is more challenging. Most of our information about horizontal stress magnitudes comes from deep boreholes, using the hydraulic fracturing technique and observations of borehole failure (breakouts and tensile cracks; see Zoback and others, 2003). Additional stress data come from stress relaxation measurements made in deep mines. The deepest measurements were made in the KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) scientific borehole, eastern Bavaria, Germany, and extend to a depth of about 8 km (Brudy and others, 1997). Stress measurements worldwide indicate that the two horizontal principal stresses increase approximately linearly with depth, as is the case for the vertical stress. Moreover, in-situ stress magnitudes have been compared to laboratory experimental friction results (for example, Brace and Kohlstedt, 1980; Townend and Zoback, 2000) to find that the crust appears to be close to a failure state nearly everywhere. This experimental observation is consistent with the idea that the Earth's crust is extensively faulted and can deform by frictional sliding. Moreover, the crust is continually undergoing strain accumulation, at quite a slow rate in tectonically stable regions and at higher rates in tectonically active regions. The result of this long-term strain accumulation is that the crust is always near a failure state and releases strain whenever the yield stress is reached. In a seismogenic region of the crust (much of the uppermost ~15 km), this strain release appears as an earthquake sequence (mainshock and aftershocks). Other evidence in support of the hypothesis that the crust is near a state of failure nearly everywhere includes the observation that earthquakes can be triggered by remarkably small stress changes imposed on faults (for example, Reasenber and Simpson, 1992).



**Figure 2.** Shear strength of the crust based on laboratory friction experiments for the upper crust (upper 14 to 15 km) and experiments at high temperatures and pressures for the lower crust where deformation is ductile. The strength for strike-slip faulting can be anywhere between the reverse- and normal-faulting regimes. In this figure, shear strength is defined as the difference between the maximum and minimum principal stresses (from Scholz, 2002).

The laboratory friction results shown in figure 2 provide some information about the horizontal stress magnitudes. The line for a normal-faulting regime (labeled “normal”) indicates the difference between the vertical principal stress and the minimum horizontal principal stress. For a reverse-faulting regime, the line shows the difference between the maximum horizontal principal stress and the vertical principal stress. Because the vertical stress can be readily estimated for any depth, as noted before, it is easy, from the information in the figure, to estimate the minimum principal stress for the normal-faulting regime and the maximum principal stress for the reverse-faulting regime. For a strike-slip regime, neither horizontal principal stress can be inferred because the line labeled “strike slip” can fall anywhere between those for normal and reverse regimes. Although generalizations can be drawn about proximity of the crust to failure from this type of analysis, it is important to note that for a particular fault to be activated in response to fluid injection requires that it be well oriented for frictional failure in the local tectonic stress field.

In brief summary, we know that the vertical principal stress can be calculated for any depth, and we also know that laboratory friction experiments (fig. 1) are reasonably consistent with in-situ stress measurements in deep boreholes. These deep borehole measurements, in concert with the observation that earthquakes can be triggered at low applied stresses, indicates that the crust is near a failure state nearly everywhere. Taken together, this information can be used to estimate, at least approximately, the magnitudes of the maximum and minimum principal stresses at depth that are valid for most rock types for normal- and reverse-faulting regimes; for strike-slip regimes, the maximum and minimum principal stresses fall somewhere in the range between the normal and reverse results. If direct information on stress orientations is lacking for a particular area, then the orientations of the horizontal principal stresses can be estimated by comparison with nearby data that might be available through the World Stress Map Project ([http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction\\_frame.html](http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html)).

## **Conclusions**

Because the state of stress in much of the Earth's crust appears to be close to failure, the safest assumption is that any amount of fluid injection could produce some earthquakes. Knowing that it may be possible to induce some earthquakes, however, is not enough. It is also important to be able to estimate the maximum likely earthquake that might be induced by a particular injection operation and measure the seismic response of the rock mass to injection. That is, one needs to be able to estimate the distribution of earthquake magnitudes, including the maximum magnitude, likely to result from a given injection activity. To accomplish this goal, it is first recommended to determine the in-situ stress field in relation to the orientation and extent of potentially active faults, especially large faults capable of producing damaging earthquakes (fig. 1). Then, in order to monitor the injection disposal operation, a local seismic network should be installed before commencement of injection that is capable of recording and locating earthquakes over a wide magnitude range. Monitoring induced earthquakes in this way will allow comparison with the injection-time history, as well as with background seismicity, and will also help define the subsurface geometry of large-scale active faults that comprise the greatest hazard. With information provided by a seismic network, the contribution of the induced earthquakes to the ambient seismic hazard can be assessed.



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